

## ABSTRACT

Title:

### **CLOSED LOOP SYSTEM IDENTIFICATION OF POSTURAL CONTROL WITH BILATERAL VESTIBULAR LOSS**

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Human upright stance can be characterized as a combination of feedback and plant. Feedback consists of integrated sensory signals, producing estimates of position and velocity of the body segments while plant includes both musculotendon dynamics and body dynamics. Separating plant and feedback is possible mathematically through closed loop system identification. By studying bilateral vestibular loss (BVL) patients it is hoped knowledge regarding human posture and the role of the vestibular system will be gained. Two BVL patients and two age, height and gender matched controls had visual and mechanical perturbations applied simultaneously to determine these properties. Both leg and trunk kinematics and EMG data were collected. Using frequency response functions plant and feedback properties were calculated. Plant and feedback dynamics differ. BVL patients show more variable weighted hip EMG data, supporting the idea that this population can not properly use hip movement with their lack of vestibular system.

CLOSED LOOP SYSTEM IDENTIFICATION OF POSTURAL CONTROL WITH  
BILATERAL VESTIBULAR LOSS

By

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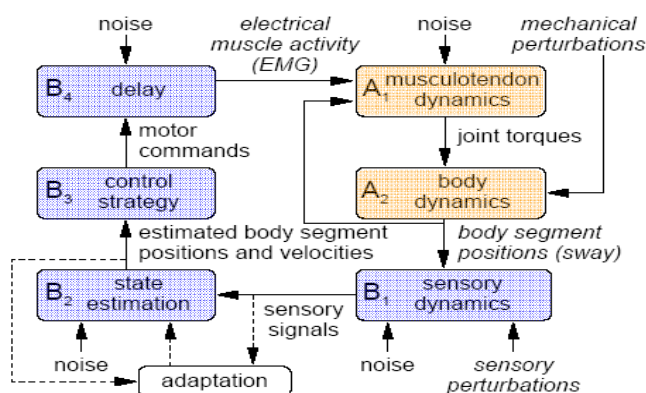


# Chapter I

## Introduction

Our ability to stand upright seems quite simple in nature but the science behind it quickly proves otherwise. Upright posture is maintained through a complex closed loop feedback control system, consisting of the plant and feedback. The constant communication between these two allows the human body to adjust to internal as well as external perturbations. On their own both the plant and feedback portions are considered to be under open loop control. The plant is considered to be the musculotendon dynamics and body dynamics. Feedback is the visual, somatosensory or vestibular systems that the central nervous system uses in order to estimate self-motion and the appropriate motor commands to maintain upright stance. When neurological or any physical traumatic injury leads to poor balance, it is difficult with current techniques to trace the instability to a particular portion of the control loop. For example, the vestibular system has both sensory and motor components, thus it is currently unclear how plant and feedback properties change with loss of the vestibular system (Kiemel et al, 2008).

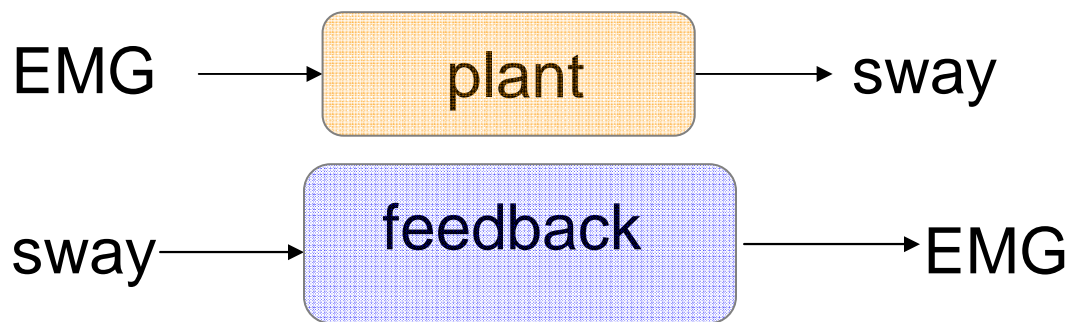
In Fig.1 a schematic is shown of the plant and feedback components for the closed loop postural system. The orange boxes represent components of the plant while the purple



boxes represent components of the feedback. In order to investigate the parts of this system one can take away the visual, vestibular and somatosensory

**Figure 1.1. Schematic of human posture closed loop system**

systems leaving the plant alone for inspection. The dilemma left here is that it is impossible for a human to maintain upright posture with the loss of all three of those senses. Before all hope is lost there is still yet another way to investigate both feedback and plant dynamics while leaving the closed loop postural system in tact. Fitzpatrick et al (2006) investigated the closed loop system of normal healthy controls using galvanic stimulation to study the plant components and a mechanical perturbation at the waist to investigate the feedback dynamics. This experiment is similar in that a sensory perturbation as well as mechanical perturbation will be used to tease apart the postural closed loop system but a visual perturbation instead of galvanic stimulation will be used to probe the plant while two mechanical perturbations will be used to investigate the feedback open loop. Further detail will be given later for the reasoning behind the use of two motors in this experiment as opposed to the one motor perturbation, which was used by Fitzpatrick.



**Figure 1.2- Basic plant and feedback schematic**

Figure 2 shows the rudimentary idea behind how the plant and feedback components can be investigated. In a very basic manner it is understood that the plant consists of EMG signals which create sway. For the purposes of this project it is believed that the EMG is a proxy of the brain therefore, by understanding the EMG signals we really understand what the brain is, or is not, commanding. Feedback in turn results from sway of the body

which creates EMG signals, the brain's way of maintaining upright posture when introduced to an outside perturbation. This is very elementary compared to the bigger picture but it efficiently explains the idea behind Figure 1. Again, both figures are color coded to allow for easier understanding of the plant (orange) and feedback (purple). In Figure 1 the orange box labeled "A2. Body Dynamics" a mechanical perturbation is applied (though in this case there are two mechanical perturbations). One will be applied at the waist while the other is applied at the shoulder. The reason for two mechanical perturbations instead of the one, as was used by Fitzpatrick, is due to the fact that for this experiment it is believed that human posture works from a double inverted pendulum system. When standing upright a tiny little push only requires humans to sway about the ankle to stay upright. A larger perturbation, such as a strong push, requires much more than an ankle strategy to stay upright, causing the nervous system to call on the hip strategy to stay upright. Therefore, this experiment is investigating two kinematic segments (the legs and trunk) with this belief and the only way to correctly explain this is through the use of two mechanical perturbations. This will be explained more a little further on.

With the introduction of the mechanical perturbation to the body dynamics, which are the orientation of the joint angles and joint torques, there is a change in body position. This change in body position is sensed by two different areas of this diagram. It is sensed by the box labeled A1- musculotendon dynamics. Here the change in body position is sensed and EMG signals are created to produce muscle contractions to change the body position. A signal from the musculotendon dynamics is then sent to the body dynamics to change the body position. This open loop would be the plant representation.

As was mentioned, the change in body position is sensed by two areas and the other area is the sensory dynamics, which consists of the three key senses- vestibular, somatosensory and visual. In other words the change in body sway is picked up by these senses. The information regarding the current sway action that has been interpreted by the three different senses is then combined using sensory integration in the state estimation box (B2). From here estimations of what should be the proper body segment angles to counter these new perturbations to avoid a fall are sent to the control strategy box (B3) which then sends out an actual motor command. Due to the complex properties of the body a delay is introduced but the command signal then makes its way to the musculotendon dynamics to create proper EMG signals.

Since the plant is part of the whole control loop along with feedback but can also be investigated on its own (unlike feedback) it's possible to mathematically extract the plant portion of the loop leaving only the feedback portion. Extracting the feedback component is impossible to do otherwise, as taking away all possible feedback from a human leads straight to falling.

To mathematically identify the features of the plant and feedback components the joint input-output approach (van der Kooij et al., 2005) was used. What makes this method more applicable than other methods is the fact that it allows for identification of both the plant and feedback using sensory and mechanical perturbation instead of a direct relationship between EMG and kinematics or vice versa (Kiemel et al, 2008). For this analysis frequency response functions (FRFs) need to be calculated. Equations 1.a and 1.b are the FRF in terms of Fourier transforms.



$$1.a \quad Y(f) = P(f)U(f) + M(f)D(f) + N_y(f)$$

$$1.b \quad U(f) = F(f)Y(f) + S(f)V(f) + N_u(f)$$

The top equation speaks in regards to  $Y(f)$  which is the fourier transform of  $y(t)$  (which describes the kinematics of the segments). The top equation states that sway is determined by three things: the control signal  $u(t)$  which is really a weighted EMG signal, the mechanical perturbation of  $d(t)$  as well as a part due to noise,  $n_y(t)$ . It must be understood that  $U(f)$ ,  $D(f)$ , and  $N_y(f)$  are all fourier transforms of  $u(t)$ ,  $d(t)$  and  $n_y(t)$ .  $M(f)$  describes how the perturbation effects the kinematics.

The lower equation states that the control signal consists of three parts as well: a part due to sway  $y(t)$ , one part due to the sensory perturbation  $v(t)$  and one part due to  $n_u(t)$ .

Again it must be understood that  $Y(f)$ ,  $V(f)$  and  $N_u(f)$  are all fourier transforms of  $y(t)$ ,  $v(t)$  and  $n_u(t)$  respectively.  $F(f)$  describes how sway influences the control signal and  $S(f)$  describes how the sensory perturbation affects the control signal.

In order to solve the first equation one can rearrange things to give the following equation:

$$2.a \quad H_{du}(f) = F(f) * H_{dy}(f)$$

Here  $H_{du}(f)$  refers to the FRF of the mechanical perturbation to the control signal, or EMG. It is a 1x2 closed-loop matrix.  $F(f)$  is the FRF for feedback.  $H_{dy}(f)$  describes the mechanical perturbation to the kinematic signals. This closed loop matrix is 2x2.

The reason for the 2x2 dimensionality is because it is assumed that the kinematic organization of the body is based on a two segment system, a trunk segment and a leg

segment. With their being two segments there must be two mechanical perturbations in. To solve for  $F(f)$  one simply divides  $H_{du}(f)$  by  $H_{dy}(f)$  to give the equation

$$2.b \quad F(f) = H_{du}(f)H_{dy}(f)^{-1}$$

With this equation one can now solve for the inferred open loop for the feedback.

In order to solve 1.b one can rearrange the formula so that it reads:

$$3.a \quad H_{vy}(f) = P(f) * H_{vu}(f)$$

Here  $H_{vy}(f)$  is the FRF from vision to body segment angles and is a closed loop matrix of 2x1 dimensions.  $P(f)$  is the plant FRF.  $H_{vu}(f)$  is the FRF from vision to the control signals and is a closed loop matrix with a 1x1 dimension. To solve for  $P(f)$  one simply divides  $H_{vy}(f)$  by  $H_{vu}(f)$  to give the equation:

$$3.b \quad P(f) = H_{vy}(f)H_{vu}(f)^{-1}$$

With this equation one can now solve for the inferred open loop for the plant.

The postural control system is currently being evaluated on humans that have all three feedback senses (somatosensory, visual and vestibular). One group that has yet to be investigated with this approach is a patient population that completely lacks a vestibular system. This study intends to investigate the plant and feedback properties with bilateral vestibular loss (BVL) subjects. By conducting this experiment on patients with BVL it is hoped that properties of the plant and feedback can be identified that are unique to having the complete loss of the vestibular input to the system. It may then be possible for vestibular physical therapists and physicians to use this information to enhance their rehabilitation programs for these patients. Medical histories will be collected from each subject to insure their diagnosis of BVL (e.g., through a caloric or rotary chair test). In the experimental design, the subject will be perturbed weakly using a visual stimulus and

two mechanical perturbations (one at the waist and one at the shoulder). Two mechanical perturbations will be used to investigate the feedback property of patients with BVL while a visual perturbation will be used to help extract information regarding the plant of these patients.

The following chapters are the literature review and the methods. Chapter 2 will review the literature relevant to multisensory integration for posture as well as a look at the influence of bilateral vestibular loss on posture. Chapter 3 will detail the methods as well as expand on expected results from the study.

Specific Aim:

**1. Patients with BVL will show a different strategy as compared to healthy controls**

*Expected Result:* Creath et al (2008) found that the patients with BVL showed a new legs leading strategy, which is not seen in healthy controls. It is therefore expected that the BVL patients in this experiment will show a legs leading strategy.

The legs leading strategy may be seen in the feedback or plant component of the BVL patients.

# **Chapter II**

## **Literature Review**

### **The Vestibular System**

Moving through the world one is constantly bombarded with a barrage of visual, tactile, and other external perturbations, yet the human body manages to stay upright without losing balance. How does the brain manage to keep the body upright instead of letting it fall to the ground when introduced to a stimulus? The answer is through a combination of three sensory systems: the vestibular, visual and somatosensory (Fitzpatrick, Burke, & Gandevia, 1996; Maurer, Mergner, & Peterka, 2006; Mergner, Schweigart, Maurer & Blümle, 2005; Peterka, 2002). By using these multiple senses the human body can organize the information by down weighing certain sensory inputs that seem inaccurate and up weighing others dependent upon the reliability of the particular incoming data. This literature review will investigate the role of the vestibular system and its influence on human posture.

The vestibular structure provides the central nervous system (CNS) with two different types of information and is located in both the left and right inner ear. In particular the information is sent to the vestibular nucleus and the cerebellum. This nucleus processes the vestibular information and is what allows for very fast and direct connections of incoming information and motor output neurons. The vestibular nucleus contains four different nuclei: the superior and medial, medial, lateral and descending. Together these four allow for relay of the vestibular ocular reflex (VOR), coordinating head and eye movements together, and connecting all of the nuclei to the cerebellum.

The cerebellum has a separate job that involves watching over the vestibular processes as well as readjusting any processes as a form of recalibration. The CNS can interpret how the body is positioned as well as moving in the current environment to control stationary head and body positions. The vestibular system can also send descending information regarding how to coordinate postural movements (Horak & Shupert, 1994; Hain, Ramaswamy & Hillman, 2000). In short the vestibular apparatus works to keep the static equilibrium (maintenance of where the head is in relation to the force of gravity) and dynamic equilibrium (knowing where the body is positioned when responding to rotational, accelerated or decelerated movements) (Grabowski & Tortora, 2000).

Within this system are the semi-circular canals and the otolith organs. Though each provides vestibular information they both do so in different ways. The semi-circular canals send rotational acceleration information of the head or body. Three canals make up the semicircular system. Each of the canals is in charge of one of the rotational axis, the x, y or z and is filled with a fluid called endolymph (Dickman, 2002; Abatzides & Kitsios, 1999). The Ampulla is located at the end of each of the three canals (where the bulge is located). On top of the Ampulla are tiny hair cells and hair bundles. These are located within a gelatinous capsule, otherwise known as the cupula. When the head is rotated in a particular direction at certain acceleration or deceleration the endolymph moves due to inertial properties. For example, if the head rotates to the right the endolymph will be moved towards the left. The movement of the endolymph will therefore cause the cupula to bend, which in turn will cause the hair bundles to bend as well (Grabowski & Tortora, 2000; Wilson & Jones, 1979). When the head rotates there is a differential pressure that begins across the cupula-crista divide in the ampulla. Due

to this change in pressure it is now much higher on the side of the partition towards the direction of the rotation, causing the endolymph to move. The endolymph now presses into the diaphragm like cupula which moves the kinocelium and stereocilia, the hair cells. The kinocelium is the longest cilia adjacent to long rows of stereocilia which extend the length of the hair cell and become shorter and shorter as one moves down the length of the hair cell. The movement of this hair cell is what causes the motion transduction because this starts the opening of the ion channels. With the ion channels open potassium is free to enter the cell causing a depolarization, allowing calcium to enter at the base of the cell. This permits neurotransmitters to be released into the synaptic cleft between the hair cells and nerve fibers, permitting an action potential to be fired to the CNS (Highstein, 1996).

With two semi-circular canal systems, one in each inner ear, how does the vestibular system register when the head is turned to the right versus the left? If the head does turn to the right then the information from the right side is stimulated while the left side is suppressed. This is why the canal system is known to be complementary. When the hair cells are bent to one particular side, say the right side for example, then the connected primary afferents of the right side will be activated, leaving the primary afferents on the left side suppressed (Wilson & Jones, 1979).

The other part of the vestibular system is the otolith organs, comprised of the saccule and utricle. These respond to gravito-inertial stimulations and are complementary to each other as well (Wilson & Jones, 1979). These organs also respond to translational head movements, or linear accelerations (Dickman, 2002). Both organs contain hair cells that when bent, send messages to the CNS. Unlike the semi-circular canals these organs

do not contain a fluid. Instead there are hair bundles, comprised of stereocilia and kinocilium. These too are supported upright by a gelatinous membrane, called the otolithic membrane. At the top of this membrane are calcium carbonate crystals, which are called otoliths. These are activated quite easily if one were to tilt their head upward. When tilting the head up the gelatinous membrane falls “down hill” over the hair bundles, causing them to bend in that direction. A message is then sent to the brain allowing it to recognize that the head is tilted in an upward direction. This system also works if the head is translated in a horizontal movement, without any rotation of the head. If when driving a car, there is a need for a sudden start, the head is going to move forward, with the car, but due to the inertial properties of the otolith membrane the membrane will actually lag behind. This lagging allows for the hair cells to be bent in the opposite direction, allowing the brain to know that the head has translated forwards (Grabowski & Tortora, 2000).

The vestibular system helps with three different things: maintaining equilibrium and gaze stability, maintaining posture and maintaining muscle tone. To keep equilibrium and gaze stability the human body has the vestibulo-ocular reflex (VOR). This allows one to produce eye movements that are in the opposite direction but at the same velocity of that head movement. The VOR allows for gaze to be maintained on a particular object even when the head is moving and works in conjunction with the semicircular canals (Dickman, 2002; Hain et al., 2000). As was mentioned earlier, the side that the head is turned to becomes the excited side while the opposite becomes inhibited. This complimentary system is what allows the VOR to work efficiently. For example, if the head is turned to the right the right labyrinth becomes the excited one

while the left labyrinth becomes inhibited. The information from the right labyrinth is then sent to the right vestibular nucleus. From this vestibular nucleus the excitation signal crosses over to the contralateral VI nuclei. Two signals are then sent out from nucleus VI: one goes up to the left lateral rectus muscle while the other signal is shot through the medial longitudinal fasciculus to nucleus III. From nucleus III the signal then makes its way to the right medial rectus muscle. This entire pathway causes the eyes to move in the leftward direction as the head is turned to the right at the same velocity of the head movement (Zalewski lecture, 2009). Loss of this reflex is very common in vestibular patients and results in what is known as oscillopsia. Since both vestibular labyrinths are unable to function properly no signal can be sent to the appropriate eye muscles preventing an equal and opposite movement of the eyes in relation to the head movement. This condition prevents these patients from being able to fixate their gaze. It becomes very pronounced when these patients are trying to walk in dark areas or places with unstable surfaces, making any sort of ambulation near impossible. A good way to test for the presence of the VOR is at high frequencies since it is not really present at low ones. The VOR contains two parts, the slow and fast components. Both components work together to allow for proper gaze stability. “Velocity storage” is another common piece of the VOR. This refers to the fact that 8<sup>th</sup> cranial nerve activity is stored here and it also outputs velocity commands to produce slow phase velocities. This velocity storage is activated by the semicircular canals, visual, somatosensory and otolith systems (Raphan & Cohen, 1996). Its primary purpose is to help the VOR as the VOR does not function efficiently at low frequencies (Zalewski, C. lecture, 2009).



The vestibulo-spinal reflex (VSR) and the vestibulo-cervical reflex (VCR) help maintain posture. Both of these are descending projections from the vestibular nuclei. Patients with BVL typically have trouble with both of these reflexes, causing them to lose stability of the positioning of their heads as well as lose postural stability. The VSR also helps with muscle tone to help with stabilization (Dickman, 2002; Highstein, 1996). Another part involved in the vestibular system is the vestibular thalamus and vestibular cortex. These areas have been found to be involved in the perception of body orientation in extrapersonal space (Purves et al, 2004).

One type of vestibular disorder is known as Bilateral Vestibulopathy or Bilateral Vestibular Loss (BVL). This disorder is brought about by complete malfunction of both the right and left vestibular systems. There are many ways from which this disease can be acquired. One common method seems to be through ototoxicity. Gentamicin is a common culprit of bilateral vestibular loss. It is used as an antibiotic but has been found to wipe out hair cells in the inner ear. It has been discovered that a positive head-thrust test could be indicative of gentamicin ototoxicity (Ishiyama, Ishiyama, Kerber & Baloh, 2006). Other possible causes of this disorder are meningitis, labyrinthine infection, otosclerosis, Paget's disease, polyneuropathy, bilateral tumors, endolymphatic hydrops, bilateral sequential vestibular neuritis, cerebral hemosiderosis, ototoxic drugs, inner-ear autoimmune disease or congenital malformations. Because there are so many possibilities of how BVL can come about it is very important to view a patient's history when diagnosing as well as treating someone (Henn, 1996).

Aminoglycoside ototoxicity seems to be the common culprit for this disorder. Black et al (1987) tried to find a way to monitor patients given an aminoglycoside to

determine if the VOR appeared to deteriorate, which would suggest that the integrity of the vestibular system was being lost. Rotation examinations are good evaluations of the vestibular system compared to the caloric test (both of which will be further explained later in this section) because only the rotating tests can evaluate the vestibular system at different frequencies while the caloric can only test one frequency. Unfortunately they found that although these rotation tests are efficient at detecting a loss in vestibular function they are not as good with predicting whether there is a major decline when doing serial rotation tests after the administration of an aminoglycoside. This therefore means that the rotation test can not be effectively used to monitor the integrity of the vestibular system at the aminoglycoside has been given. One interesting point that was found was that most patients showed some capacity for recovery following the ototoxicity. There was no consistency between subjects on the level of recovery partially due to the amount of vestibular loss that had taken place. But this does suggest that even with something as devastating as aminoglycoside ototoxicity, that some sort of recovery is possible so long as the entire vestibular system has not been lost (Black et al, 1987). Though it seems that no true predictor of devastation to the vestibular system exists it is argued that bedside examinations can help detect deteriorating vestibular function as hopefully a more definitive test is soon discovered. As long as the aminoglycoside is closely monitored it is possible for physicians to detect the decline in vestibular function early enough and remove the patient from the ototoxic drug allowing the vestibular system to repair itself even back to full function (Minor, 1998).

With this vestibular disorder there are a few signature symptoms. One is their nystagmus. Nystagmus is a slow deviation in one direction, known as the slow phase,

with a rapid return, known as the quick phase. When everything is operating correctly a “normal” nystagmus would occur when moving the eyes in the opposite direction of the head and at the same velocity with the use of the VOR in order to keep one’s gaze stable on a particular object. This is the slow phase and it is induced by angular acceleration. There would then be a quick period of resetting the eyes in the direction of the head. This is the quick phase. Someone with BVL would not have normal nystagmus and would have to compensate by using saccades in order to follow an object, creating a delay in the movement of the eyes in relation to the head movement (Markham, 1996). There are ways in which to test nystagmus which will be discussed later. Oscillopsia is a very common and disturbing symptom of this disorder. Due to the faulty VOR and nystagmus, vision during movement becomes very unclear. Oscillopsia can be brought about by walking, driving and even when breathing. This symptom can be very debilitating and is usually what leads to a decrease in social and physical activities along with an increase in depression (Herdman & Clendaniel, 2000). Another common symptom is unsteadiness of gait, especially in the dark and on uneven surfaces due to the malfunctioning VOR at high frequencies (Brandt & Dieterich, 1993). A false assumption that is sometimes made with patients with BVL is that they also suffer from vertigo. This is not true. Vertigo can only occur when there is an imbalance between the two vestibular systems but since both systems are completely dysfunctional it’s impossible for there to be an imbalance, though if their BVL is limited to the horizontal canal it can be possible to have vertigo sensations due to malfunctions in either the posterior or anterior semi-circular canals (Ishiyama et al, 2006).

For initial diagnosis of bilateral vestibular loss the physical therapists must take the patient through a battery of tests that range from balance examinations to using rotary chairs. When trying to distinguish BVL from other vestibular disorders there is a particular flow of symptoms that points the physical therapist to this diagnosis. Usually when investigating the person's history there is no sign of vertigo but a feeling of disequilibrium. With a basic head thrust test, which is considered a bed-side evaluation, if the results are positive for both sides then it can be assumed that there is a possibility of bilateral vestibular loss. The head thrust test is a quick way of evaluating the state of the VOR of a patient without the use of any equipment. The medical examiner holds the head of the patient in their hands, asking the patient to focus on the medical examiner's nose. The examiner then moves the head slowly and smoothly back and forth watching the eyes of the patient. At some random point in time the examiner quickly jerks the patient's head to one side and back to the middle. By watching the eyes of the patient someone with BVL, will lose gaze focus of the medical examiner's nose, and they will show a delay in bringing their eyes back to the object of focus, thus proving that there is a problem with the VOR and the patient had to use a saccade in order to bring their eyes back to focus on the examiner's nose (Herdman, 2000). Some of the basic examinations look at somatosensory sensations as well as vision. There are also investigations of coordination, strength and range of motion, but the physical therapist must be careful when examining the patient's head movements because subjects with BVL tend to restrict those to prevent oscillopsia. Postural and positional tests are also done to make sure vertigo does not come about since that would be a negative sign for BVL. Sitting balance tests are done because it is hard for these patients to shift their weight, while an array of

static postural tests, such as the Rhomberg test are also used. Ambulation tests are very useful, as these patients are very stiff in their walking manner, especially when trying to turn corners, and have difficulty with low lighting or changes in walking surfaces (Herdman & Clendaniel, 2000).

There are a few common vestibular test batteries. These are the search for a vestibular nystagmus, an ocular motor screening battery, positional testing, posturography, caloric testing and rotational testing. This combination of tests is usually referred to as ENG (which is synonymous with EOG or electronystagmography). Of these tests the caloric is usually the most revealing with regards to the laterality of the labyrinth functions. When searching for vestibular nystagmus one is searching for a spontaneous nystagmus while being seated in the dark or while wearing darkened goggles. By removing any fixation for the patient it is easy to detect a latent asymmetry. A spontaneous nystagmus means there is an imbalance in the vestibular system that only appears when there is nothing for the patient to fixate their vision on. This is usually only seen in patients who have acute or recent onset of vestibular system abnormalities as central compensation can soon fix this (Furman & Cass, 2000; Zalewski, C. lecture, 2009).

The oculomotor screen battery tests investigate nystagmus with gaze deviation, saccades, pursuit and optokinetic nystagmus. Gaze evoked nystagmus can be investigated by measuring eye movements when having patients fixate on an object at different positions from center. Finding gaze-evoked nystagmus means there is a deficiency in the patient's ability to hold their gaze and that there is a problem in the brainstem or cerebellum. To test voluntary saccades you ask the patient to fixate on a

small target that moves in a random horizontal pattern. This is typically done with a moving laser while a computer records the eye velocity, saccadic accuracy and latency between the movement of the target and movement of the saccade. Horizontal saccades that are too slow suggest a problem with the paramedian pontine reticular formation (PPRF) while very large saccades mean a possible problem with the cerebellum (Furman & Cass, 2000).

When testing for ocular pursuit a patient is asked to smoothly follow a moving laser target. This can determine whether or not there is a problem with the VOR. What are known as “catch-up saccades” are indicative of a vestibular disorder. Symmetric ocular pursuit problems make it a little harder to diagnose the patient but asymmetric ocular pursuit problems seem to be more suggestive of a unilateral vestibular problem.

To test for the optokinetic nystagmus recording is done while the patient looks at a full-field of black and white vertical stripes that move horizontally in a constant or sinusoidal direction around where the subject is seated. Abnormal results give a localized value of disruption (Furman & Cass, 2000).

The other two tests are positional and positioning nystagmus tests. Positional nystagmus is brought about by being in any one position. The nystagmus may beat in the same direction or change directions when the position is changed. This change could be related to the fact that the alterations bring about changes in gravitational pull on the otoliths. If it can not be suppressed it suggests that there is a problem within the central nervous system. For the positioning nystagmus the Dix-Hallpike test is used and is indicative of the presence of benign paroxysmal positional vertigo (BPPV) especially when torsional up or down beating nystagmus is present (Furman & Cass, 2000).

Posturography is a clinical assessment of postural stability. This is usually accomplished with a moving platform posturography device, though with this being very expensive to acquire as well as fit in a lab Weber and Cass (1993) found that using the foam dome test can test almost the same thing with a much lower financial cost. Typically 6 different tests are done to evaluate the postural stability of patient. Test 1 has the patient stand on a stationary surface staring at a stationary visual reference with their eyes opened. Test 2 has the patient in the same situation except their eyes are closed. This combination therefore looks at the ability for the patient to stay upright with the loss of visual information. Test 3 has the patient on a stationary platform with eyes open but the visual surround is sway referenced. Test 4 has a stationary visual surround, eyes open but the platform they are standing on is now sway referenced. This tests their ability to stay upright with the loss of somatosensory information. Tests 5 and 6 are key determinants of whether or not a patient has a vestibular deficit as both require the patient to rely heavily on the vestibular system to stay upright. Test 5 requires the patient to stand upright with their eyes closed and on a sway referenced platform while test 6 requires the patient to stand upright with the visual surround and platform sway referenced while their eyes are open. Normally patients with a vestibular deficit will either sway a great deal and then fall or just fall at the start of the test for both conditions 5 and 6 therefore making those two good indicators of vestibular loss (Weber & Cass, 1993; Zalewski, C. lecture, 2009; Black et al, 1988).

The caloric test is considered the “gold standard” for diagnosing BVL and tests the function of the VOR. Its purpose is to induce endolymph flow using water or air to create a temperature gradient. The biggest temperature gradient occurs in the horizontal

semicircular canal so this test is always used on that canal. In order to perform this test the patient must have their head tilted upwards  $30^\circ$  so the horizontal canals are in the vertical plane. To do the caloric test one uses warm water and cold water, both of which give opposite results (though this test can also be done with warm or cold air). Inserting warm water into one ear will cause the fast nystagmus component to beat towards the stimulated ear. Cold water causes the fast component to beat towards the opposite ear. When conducting this test 250 cc of water are used at a time for 30-40 second periods with a 5 minute resting period between each one to be sure that any residual velocity storage is depleted. Using different conditions it can allow one to evaluate whether there is a vestibular problem or not. Normal subjects will be able to suppress the nystagmus when there is some form of fixation compared to when there is not while someone with a vestibular disorder will have trouble suppressing the nystagmus with or without fixation. When trying to identify someone with BVL with this test it is important to do the caloric test a few times with a patient (Honrubia, 2000). If a patient is suspected to have BVL and the caloric test results indicate that it could be a possibility another step must be taken. The patient is then subjected to ice water calorics. It is possible for patients with BVL to have function of their labyrinths at higher frequencies and ice water can imitate the high frequency motion. If nystagmus is present during the ice water calorics the patient must quickly be placed into the prone position. If the nystagmus fast phase switches directions this indicates that the patients with BVL does have higher frequency function and they do not have a complete loss. If the changing of position does not result in this direction change then the response to the ice calorics is likely a pseudoresponse (Zalewski, C. lecture, 2009).



Rotational testing of the horizontal nystagmus is the last of the list. This is considered a very good test because it represents more of a real situation as far as the endolymph being moved due to angular acceleration. The only problem is that this stimulates both labyrinths, unlike with the caloric test where you can stimulate one labyrinth at a time. This test works because the slow component of the velocity of rotational induced nystagmus is proportional to the deviation of the cupula, which is then also proportional to the magnitude of the angular velocity of the head movement. The three types of rotation are sinusoidal, constant and impulsive. Sinusoidal is the most commonly used because it is reproducible and the most easy to use as well as the fact that it is easily defined by a period and maximum amplitude. Results come out in terms of gains and phases regarding the responses to the rotational stimuli. The rotational test is very useful in finding out whether there is even a tiny bit of vestibular function left, which is harder for the caloric test to identify. This is important because even a tiny functionality could change a doctor's mind regarding surgical treatments for subjects with BVL. Ototoxicity effects are also easily identified by this test (Honrubia, 2000). Suppression of the optokinetic afternystagmus can also be noticed with this test and would suggest BVL (Hain, 2007; Purves et al, 2004).

When treating BVL many exercises as well as other treatments have been made in order to help improve the condition of these peoples' lives. One suggestion has been to try to improve their VOR gains. Since postural instability and oscillopsia are usually brought about due to a low gain with head movement and eye movement it has been suggested that improving the VOR gain should be a goal for these patients. Another suggestion is to strengthen the other senses. The treatments need to be catered to each

patient. Exercises facilitated by the physical therapist as opposed to home exercises are more effective (Herdman, 1997).

All of the three sensory systems work at different frequencies but only the vestibular system can work at high frequencies so strengthening vision and somatosensory for high frequencies is impossible. Therefore it is very important to improve the VOR for that range of frequencies. Reversing prism goggles have been found to be useful for this rehabilitation (Herdman, 1997). Stem cell therapy has also been suggested. It has been found that inner ear progenitor cells could differentiate into inner ear hair cells and neurons. Particular mouse cells have also been found to be successful (Martinez-Monedero & Edge, 2007).

With these symptoms physical therapists have found ways to teach patients with BVL how to compensate for their loss. One way to improve their postural stability is by having them try to stand upright with a moving visual surround. Only the vestibular system can function at high frequencies of movement so by moving this system at a higher rate it exercises the vestibular system (Herdman & Clendaniel, 2000).

Another compensation strategy is learning how to get out of bed, especially at night. The key is to wait at the edge of the bed till the eyes adjust to the lighting as well as be sure they are awake before they try to get up and walk around. Having emergency lighting in the house as well as outside is also useful to help with gait compensation (Herdman & Clendaniel, 2000).

Research has found that utilizing different types of exercises can help build the tolerance mechanism in the brain, which can help compensate for the inner ear imbalance. Some of these exercises include “ball circles”, where the subject stretches their arms out fully

while holding a ball and must follow the ball with their eyes and head. This is done while they move the ball in a large circular motion in front of them. Another exercise is called the “ankle sway” where the patient stands with feet shoulder width apart and rotates forward and backwards as well as side to side about the ankle, without bending at the waist. A final example is having the patient walk a few steps, turn their head to the right and walk a few steps and then turn their head to the left and walk a few steps. This allows for them to adjust to the forward motion of walking with the addition of having their head angled in different directions (Abatzides & Kitsios, 1999). The use of a cane as a form of light touch, rather than something to lean on for physical support, has also been suggested as a rehabilitative aid for vestibular patients (Jeka, 1997). It is very important, though, that when giving out exercises that the degree of dizziness that accompanies these workouts is taken into account with each patient. It needs to be explained that these patients will feel an increase in dizziness with doing these exercises but it will go away only if they are persistent in attacking the program. The exercises can be made longer and the frequency of movement can also be increased to make them more challenging as the patient begins to improve (Herdman & Clendaniel, 2000).

These patients rely heavily on visual and somatosensory information in order to keep their balance. Patients who have not learned to compensate for the loss of this sensory organ have trouble staying up right when either vision or somatosensory information is taken away. Age may be a possible factor as to why some people may not be able to integrate remaining senses for balance, as was found with normal healthy subjects above the age of 50-55 with somatosensory organization tests (Peterka & Black, 1990).

Another way these patients attempt to stay balanced is through the use of the ankle and

hip strategy. The ankle strategy is the idea that a human, when perturbed a tiny amount, will only sway about the ankle, provided that the sway does not linger near the edge of that subject's base of support. When the subject is then introduced to a larger perturbation, one that brings their center of mass (COM) near the edge of their base of support, that subject will use a hip strategy and rotate about the hip joint to keep balanced. Since many subjects with BVL have little control over the coordination of their head and trunk they will over rely on the hip strategy. This could be for many reasons. One is that these patients may be over sensitive when this hip strategy is invoked. Their vestibular system may also not be able to accurately estimate the velocity at which the head and trunk is moving in the anterior-posterior directions. Another thought is that some of these patients have lost the somatosensory information in their feet, therefore causing them to rely on the hip strategy a lot since they can not get any information from their lower limbs. Finally, there could also be an internal inaccurate representation of that subject's stability limits. Therefore, when the vestibular system senses a perturbation that could compromise the body's balance causing it to not react properly even if the perturbation is not detrimental (Horak & Shupert, 1994). Runge et al (1998) actually found that BVL subjects were able to utilize the hip strategy with the initiation of rapid postural responses. They believe that other experiments may have found opposite results due to the fact that their patients with BVL could not map well. Therefore, not all patients with BVL are incapable of utilizing the hip strategy for balance; it may be that some are more predisposed to being able to use it due to their particular condition. Runge et al drew the conclusion that the vestibular system may not be necessary for selecting and triggering a hip strategy but they do not deny the

possibility that the vestibular system can help control hip strategy in particular situations (Runge et al, 1998).

Kuo (2005) investigated the role of the vestibular system in the control of human posture by creating a model that would simulate state feedback control and optimal state estimation. He found that his state estimator and state feedback model may be good for predicting the stance of subjects with BVL. When comparing his model with experimental data he found that his model was able to represent the robust reactions of the normal patients when they had sensory perturbations that caused them to sway more. He then tried to model patients who had both canal and otolith sensors that were dysfunctional in both ears, representing patients with BVL. This model remained stable as long as vision and proprioception stayed accurate. He then found that when this model was missing proprioception or vision that it became very unstable, accurately representing that of patients with BVL reaction. When the model was deprived of both vision and proprioception there was only a slight more increase in the sway of the model as compared to taking away just proprioception or vision. This model accurately represented how a patient with BVL would react to having one or both sensory systems distorted. He therefore concluded that the model was able to predict that the loss of one sensory modality for subjects with BVL has a large effect on balance, while disrupting both of the remaining two senses with these patients did not compromise their stability much more(Kou, 2005). Even with the loss of their vestibular system the brain can still integrate information from the other two senses to maintain balance. This idea of multisensory integration is paramount in order to understand postural stability.

## **Multisensory Integration and its Influence on Posture**

The ability to maintain balance is through the product of the input of the visual, proprioceptive and vestibular inputs (Purves et al, 2004). The integration of these three senses is referred to as multisensory integration (Allison, Kiemel & Jeka, 2006; Fitzpatrick et al 1996; Maurer et al., 2006; Cenciarini & Peterka, 2006). How these three senses are combined is still unknown as far as whether or not their inputs are evenly used or whether one dominates over the others during particular situations. It has been found that these senses may not work in a negative feedback control loop and may rely on feed-forward processes. This may be why patients who lack a vestibular system are unable to properly react to a balance disturbance because they can not create the necessary response due to the lack of this feed-forward response (Fitzpatrick et al., 1996). Maurer et al. (2006) have found, through the use of modeling that normal healthy subjects were able to down weight, or ignore, particular sensory information when it was considered to be inaccurate and rely on the other information in order to keep them selves balanced. This would suggest that the CNS does seem to rely on some sensory systems more than others in particular situations. Cenciarini and Peterka found this to be true when testing to see if galvanic stimulation (GVS) sway response would increase when increasing sway or proprioception amplitude. This indeed was the case, showing that the CNS was able to reweigh the senses when it became necessary (Cenciarini & Peterka, 2006).

Oie, Kiemel and Jeka (2001) tested the idea of sensory reweighing by using a model of sensory reweighing as a mechanism in multisensory fusion. By using vision and touch stimuli at particular ratios they found intro-modality and inter-modality dependencies, which showed that there was no control strategy but a change in sensory weighting across

sensory conditions (Oie et al., 2001). This seems to hold up across age groups, even with the fall prone elderly (Allison et al., 2006).

Unlike healthy subjects Peterka (2002) found different multisensory reweighing results when comparing subjects with BVL to normal subjects when applying a visual stimulus. Application of visual stimuli to normal subjects would cause them to couple to the visual information, provided that the input amplitude was low. When the amplitude grew to be too large the normal subjects hit what Peterka referred to as a saturation point, meaning the normal subjects no longer coupled to the visual display. This is because the CNS of the normal subjects realized that the visual information being provided was false and it therefore down weighted the visual information and relied on the proprioceptive and vestibular information that was available. This was not true for the patients with BVL. When these subjects were introduced to the visual stimuli they never hit a saturation point. In fact, their gain ratio of their sway to visual amplitude was linear (unlike the non-linear fashion of the normal, healthy subjects), showing that even with an increasing amplitude the CNS was unable to recognize the need to down weight the false visual information, due to the absence of vestibular information. As a result the subjects with BVL increased their stiffness to compensate for the lack of vestibular information (Peterka, 2002). With this lack of vestibular processing and faulty visual information the only information left for the CNS is from the proprioceptive system. Having only one system available has been found to not be reliable enough in order to maintain posture (Peterka, 2002; Kou, 2005; Basci & Colebatch, 2005).

Fitzpatrick and McCloskey (1994) made an argument that the vestibular system may not be needed for posture. They stated that normal healthy subjects can not perceive normal

body sway with their vestibular systems and rely on proprioception or visual information. They found that the vestibular system had a higher displacement threshold for the perception of movement that occurred about the ankles and was also much greater than that of the visual and proprioceptive thresholds. This allowed them to draw the conclusion that the vestibular system may not provide information regarding normal sway. They also found that multisensory integration may not be an additive function, that all of the modalities are redundant if all of them are available, unless one is much more sensitive than the rest. This conclusion would then mean that the results found by Peterka (2002) can not conclude that a lack of vestibular system with these patients is why they were less stable.

The ability to reweigh sensory information is a problem for patients with BVL because they have completely lost one of these systems. Much has been done in order to help enhance their abilities to maintain posture as well as to probe their stability limits with the loss of their vestibular system

### **Investigations of Postural Stance with loss of vestibular system**

As has been stated the vestibular system is a key component to posture. Without it the ability to stand upright becomes more difficult. It may also be true that patients who lack this sensory system will transition between sensory states much more slowly, causing them more instability (McCollum, Shupert & Nashner, 1996). Many studies have been conducted to investigate how vestibular patients react to different sensory environments. Mergner, Schweigart, Maurer and Blumle (2005) investigated how subjects with BVL would take to visual perturbations while standing on a stationary



platform, a sway referenced platform and a laterally tilted platform. They found that the subjects with BVL showed the same gain response on the stationary and laterally tilted platforms as the normal subjects, except that the subjects with BVL had much stronger gains. With the sway referenced platform the subjects with BVL showed an abnormal increase in gain over the normal subjects. This suggests that with the loss of ankle proprioception from the sway referencing and the distortion from the visual signal that no sensory information could be sent to the CNS to help maintain balance in that current environment.

Nashner, Black and Wall (1982) went even further and suggested that the vestibular system is at a hierarchically higher level than vision and proprioception. They do not feel that the reason these subjects with BVL can not keep balanced when introduced to faulty visual and proprioceptive information is true. In fact they believe that the “vestibular inputs provide the orientational reference against which conflicts in support surface and visual orientations are identified rapidly.” With their loss of the vestibular system there is no way to check the sensory information coming from the other sources since the vestibular system no longer exists.

The fact that subjects with BVL have one less sensory system to rely on for postural information is a reason for their balance complications but could there also be a possibility that these patients have fewer control strategies compared to normal healthy subjects? A study by Creath et al in 2002 ventured for an answer. It has been found that passive, light touch of less than one Newton applied by a finger can help with postural support (Jeka, 1997; Rogers, Wardman, Lord, & Fitzpatrick, 2001). This group took that idea a step further to see if subjects with BVL showed less control strategies than normal

subjects due to an inability to reweigh incoming sensory information. Subjects stood on a rotating force platform while maintaining light finger contact on a touch plate. The touch provided the same amount of stability for both groups but when comparing control strategies of coupling finger movement with center of mass movement the normal subjects were able to uncouple their finger movement from the center of mass movement at higher frequencies. Patients with BVL were unable to do this, which meant they were unable to down weight that information when the frequencies increased. Since these subjects had their eyes closed and had no vestibular resource they were forced to have to couple to the platform.

Aside from the fact that movement of the support system influences the stability of these vestibular patients it has also been found that the direction of the platform movement may be worse than others. By changing the direction of the platform movement there was a selection of stretched or unloaded muscle groups. Subjects with BVL seemed to have trouble with roll directional movements of the platform more so than pitch, especially if the roll direction was tilted more to the back. When the platform went in this direction these subjects had an increased velocity in that direction compared to normal subjects. Since their vestibular system is no longer in tact there is nothing to inhibit this response, which is usually inhibited by the vestibulo-spinal pathway. These results suggest that patients with BVL are worse off with roll movements of support surface plainly due to the fact that they no longer have a proper vestibulo-spinal pathway (Carpenter, Allum, & Honegger, 2001).

Studies have also been done by groups to see the effects of posture on bilateral vestibulopathy in cats. Stapley et al compared cats before and after bilateral

labyrinthectomy to compare their balance for voluntary head turns. Before the surgery the cats were trained to be able to turn their heads in a rapid and large amount in a particular direction in the yaw plane. They found that the cats had trouble with their balance after the lesion. When the cats moved their heads they found that they would extend the muscles on the opposite side, causing them to fall. They concluded that the lack of vestibular input was the reason for their destabilization after the voluntary head turn. Since the vestibular system was absent the cat's nervous system was creating the wrong "corrective" postural stance. The cats also seemed unable to pick up any roll motion that the body was making which suggests that the neck proprioceptive input of head-on-trunk is read as the body rolling under the head, which means the cat thought their trunk was falling when indeed it was not (Stapley et al., 2006). An interesting note though, was that 40 days after the lesion the cats did seem to adapt and were able to run around the lab with much more ease compared to right after the lesion. Could this be further proof that adaptation is possible for bilateral vestibular loss?

Another group investigated how the automatic postural response (APR) of bilateral vestibular loss cats would change with rotation of support surface. They found that the cats had problems maintaining balance during platform rotation. This imbalance seemed to be brought about by an improper APR response. Not only was it improper but it was the complete opposite of the normal response! When looking at the EMG recordings after the lesion, the EMG for a particular muscle would fire during the APR time period when it was not supposed to be, while the ones that were supposed to fire stayed dormant. For example, if the platform was moved into a "downhill" position the cats would actually push themselves downhill causing them to fall. Therefore, a reason patients with

BVL may have problems with the APR is because of the loss of the proper vestibular input (Macpherson, Everaert, Stapley & Ting, 2007).

One possible reason for the inappropriate APR could be due to the loss of the ability of the labyrinthine to inhibit the extensor muscles as it normally would do. Since the labyrinthine no longer functions it is thought that the spinal reflexes may step in to try to keep the body stable and may as a result create the obvious forward-backward sway that is seen by these patients (Tokita et al, 1988).

Is it possible to look at the postural stability of patients and determine the functionality of the vestibular spinal reflex responses and therefore classify the patient as being either normal, unilateral or bilateral in their loss? Allum et al (1988) investigated EMG responses in the ankle and neck muscles as well as the amplitude of ankle torque responses to determine underlying tips on pin pointing the laterality of vestibular loss for patients. In order to get responses the experimenters had the patients stand on a platform that elicited ankle dorsiflexion (toes-up direction). They found that overall the patients with BVL showed significantly weaker reactions. When looking at the mean amplitudes for ankle EMG the smallest amplitudes were found with the weakest patients, those with BVL. UVL patients with an acute disorder would be slightly better followed by UVL patients with compensation. The largest responses therefore came from the normal subjects. This gradation was seen even more clearly when this was done with the subjects' eyes closed. This same gradation was seen as well with ankle torque even with the eyes open as well as with the neck extensor activity. With this experiment they found statistically supported evidence that reduction in the strength of the vestibular signals created a weak response in ankle muscles which would in turn create a weaker ankle

torque as compared to normal subjects. This caused the patients with BVL to fall backwards during the ankle dorsiflexion, especially during eyes closed trials thus allowing for a gradient that clinicians could use to determine the level of dysfunction exhibited by the patient.

Coordination of movement between body segments has also been investigated to see if any sort of pattern emerges making it possibly easier to diagnose someone who may have a bilateral vestibular loss. Nashner et al (1988) investigated the head and body movements of subjects who performed postural tasks with different movement patterns. This was done to try to determine how normal subjects behaved. For this experiment postural sway was induced in two different manners. Subjects stood on a sway referenced platform with their feet fixed so that any head or trunk acceleration forward was due to the influence of gravity. These were called the free-fall trials. The second way postural sway was induced was through “perturbed” sway trials. Here the upper body was stationary from the start but the feet were displaced unexpectedly backward by translating the platform. They found that during active postural movements of the platform that occurred at the hip, the trunk and head moved together in order to keep the body stable. This would suggest that control of the head and body is coordinated during hip movements. Smaller movements on the body, such as those that were created during the free-fall trials, showed the normal subjects compensating by swaying about the ankles. Here the trunk and head movements did not appear to be coordinated. This could be due to the fact that the perturbation was smaller and only initially about the ankle, therefore, it would take time for the rotation of the body about the ankle to make its way up the body to the head, thus causing a delay in the head movement in comparison to the

trunk. They concluded that head and body movements are coordinated independently of each other during active ankle movements. It could also be that the nervous system has no need for anticipatory head movements like it would with a movement that causes the hip to sway, since the “head orientation remains within tolerable limits.” It was also suggested that patients with a distorted vestibular function become very unstable when given incorrect sway referenced information (Nashner et al, 1988). Therefore, they may show the correct ankle strategy as they will use that to also get touch information from the floor they are standing on but are not as capable of using the hip response pattern, possibly because it involves the coordination of the head and trunk (Black, et al, 1988). Though some patients with BVL may not use a hip strategy other patients with BVL still do use the hip strategy. Why the difference in the same patient population? Black et al (1988) ventured forth to figure out why this difference existed within the same population. The experiment was conducted using the posturography examination (all 6 conditions were explained early in the literature review). After looking at their results they classified their patients into 3 different categories. Category 1 meant that the patients swayed within normal limits for conditions 1 and 4 but were consistently abnormal in conditions 5 and 6, which heavily rely on the use of the vestibular system in order to stay upright. This is where the majority of the patients with BVL were placed. Category 2 patients used excessive postural sway in conditions 3 and 6 but would be fine for condition 5. Category 3 patients would show a combination of these other two patterns. All 6 conditions of the posturography exam were conducted along with a test of their responses to a brief, constant velocity platform translation while standing either on a normal support surface or while standing across a narrow beam.

The patients with BVL for the most part would respond normally to support surface perturbations and use the appropriate coordination of the legs and trunk while swaying about the ankle. When standing on the narrow beam, with the ankle pattern no longer effective, all patients with BVL could not (or possibly would not) switch to the proper hip strategy. The category 1 patients were made up of a majority of patients with a loss of the vestibular system and would sway about the ankle with the hips held very rigidly. The category 2 and 3 patients for the most part had vestibular distortions rather than vestibular losses and would show a greater use of hip sway. It is possible that the reason many of the patients with BVL do not use a hip strategy is because the hip movement causes the head to move forward even though the hips are moving backward which is unlike sway about the ankle where swaying backwards would cause the body as well as the head to move backwards as well. Therefore, movement at the hip would require a completely new reinterpretation of the vestibular, visual and somatosensory information that is coming in to stay balanced making it hard for a patient with BVL to stay upright (Black et al, 1988).

It is apparent that without the vestibular system there is less feedback information for the CNS to make a reliable decision on how to maintain stability. Could it be possible for external feedback sources to be used to help compensate for this sensory system loss?

### **Possible Feedback Mechanisms to Replace the Loss of the Vestibular System**

Many different types of feedback mechanisms have been attempted to help enhance the stability of vestibular patients. Investigations from cognitive modulation to auditory and vibrotactile feedback have tried to find an answer. This section will serve to enlighten the reader on what has been done scientifically to help advance knowledge towards a postural stability method for vestibular loss patients.

Guerraz and Day (2005) investigated whether or not the vestibular system was susceptible to cognitive modulation as they had found was true for the visual system. To test this they used Galvanic stimulation (GVS). This technique uses electrodes that are placed on the mastoid processes to send a small current to the vestibular system. GVS can cause a subject to either sway or perceive false movements. In general it produces a signal of head movement, which is not really occurring, and in turn affects the motor control of the body (Fitzpatrick & Day, 2004). Guerraz and Day found that no matter whether there was expectation of a vestibular stimulation from a self-trigger condition or from a predictable condition due to prior knowledge of timing cues, the knowledge of the GVS signal had no effect. When testing this with vision being available to the subject the same results were still obtained. Therefore, no help can come from cognitive methods for aiding in the loss of the vestibular method at least according to this experiment.

Auditory biofeedback has also been investigated as a possible solution to the lack of vestibular information these patients have. Dozza et al (2005) investigated whether or not the Auditory Biofeedback (ABF) system was causing an increase in stiffness that was allowing these patients to stay steadier or whether or not there was another strategy



taking place. The ABF system was applied through a headset worn by the subjects. If the subject moved in the anterior-posterior direction the sound pitch would change (an increase in pitch for forward sway and a decrease in pitch for backwards sway). A tilt in the lateral direction would result in one ear getting a louder sound than the other.

Therefore, if a subject leaned to the right the sound level would be higher in the right ear phone than the left. If a movement was made in the forward, right direction there would be a higher pitch noise that was supplied more to the right ear phone. All subjects were given adequate time to learn how to use this ABF system before beginning the actual trials. All trials were done on a foam support with eyes closed. By using stabilogram analysis diagrams and EMG recordings they were able to find that subjects with BVL were not using a stiffness strategy in order to stay balanced. In fact these diagrams showed there was a more regulated control system being used to reduce the COP sway. This suggested that the brain used ABF for a form of feedback based control.

Dozza, Horak and Chiari (2006) investigated how subjects with BVL, along with controls, would react to ABF with lowered vestibular, somatosensory and visual inputs. They found that all of the subjects benefited from the ABF system, no matter the severity of their vestibular loss. In fact the more of a vestibular loss that was present the more improvement there was from the assistance of the ABF system. An interesting note was that subjects who normally preferred to rely on somatosensory information would utilize the ABF more when they lost somatosensory information compared to when they only lost visual information. The opposite was true for the visually dependent subjects.

Overall, the patients with BVL showed a significantly higher rate of postural corrections over the controls in all possible conditions, suggesting, again, that the subjects with BVL

were using a different control strategy from the control subjects, as was stated earlier in reference to the Creath et al (2005) findings.

Another form of external feedback information that could be used in replacement of the vestibular system is by use of vibrotactile prosthesis. This type of feedback would provide sensory knowledge to the somatosensory system, to help increase the amount of information, regarding the subjects' posture, being sent to the CNS. Kentala, Vivas and Wall (2003) tested 6 subjects with either UVL or BVL to see whether vibrating tactors placed on the abdomen and back could help improve their posture. Three tactors were placed in a vertical row on the abdomen and three were placed vertically on the back of the subject. If the subject leaned forward the abdomen tactors would buzz and likewise, if the subject leaned backwards, the tactors on the back of the subject would buzz. If the amount the subject leaned in the AP direction was between 1-4 degrees only the lowest of the tactors would buzz. If the subject leaned between 4-7 degrees in the AP direction the lowest and middle tactors would buzz. Any tilt greater than 7 degrees, forwards or backwards, would result in all three tactors buzzing on the appropriate anterior or posterior side of the subject. All subjects had time to adjust and practice using these tactors. The results showed that even the worst of all the vestibular subjects (i.e.- subjects who were unable to stand on their own to their vestibular deficiency) were able to stand throughout the entire test when the tactors were used. A significant decrease in AP sway was seen with all vestibular subjects. Wall and Kentala (2005) found very similar results when testing this tactile device on their vestibular subjects. They too found it to improve balance across the disease severity spectrum of their participants and

found that this control was gained between 0.56 and 0.71 seconds after the tactors began to buzz.

A tactor on the tongue has also been suggested as a useful rehabilitation tool. The BrainPort is balance device that is used on the tongue that substitutes the vestibular system. Tilt data from an accelerometer is used to drive the position of the stimulus pattern of the actual BrainPort. They found gait to improve in all 40 of their subjects and it even showed retention effects provided the tool was used enough by the subjects. There even seemed to be some transfer into other functional dynamic activities (Danilov, Tyler, Skinner & Bach-y-Rita, 2006).

## **Conclusion**

The vestibular system plays a paramount role in the ability to maintain stability and posture through the use of multisensory integration. The loss of this sensory system leaves only somatosensory and visual senses for CNS control of posture. Research has found that removal of one of the remaining two systems makes balance for these vestibular patients nearly impossible. Science is working toward finding external sources of information that can be used to enhance the two remaining intact sensory systems as well as to provide additional information. So far both ABF and vibrotactile stimuli seem to provide strong, reliable information to the CNS, and help stabilize even the most severely affected vestibular patients. GVS has also been found to help stimulate the faulty vestibular system. Recent advances indicate that a possible solution for these vestibular patients may be on the horizon.

# Chapter III

## Introduction and Methods

### Introduction

Quiet stance is maintained through a delicate balance between the communication of the plant and feedback dynamics in closed loop postural control. Through the combination of feed-forward commands and the interpretation of external somatosensory, visual and vestibular information the human body is able to maintain balance while standing (Fitzpatrick et al., 1996; Maurer et al., 2006; Mergner et al., 2005; Peterka, RJ, 2002; Kiemel et al, 2008). It is when one of these significant components is damaged, or all together missing, that this seemingly simple task becomes almost impossible.

### *Rationale*

The workings of the nervous system are fairly well understood as far as multisensory integration is concerned but how does the nervous system fair when one of the three sensory systems is severely failing if not completely missing all together? Bilateral vestibular loss is a condition where the vestibular system is almost if not completely absent due to either a prior inner ear sickness, head trauma, ototoxicity, etc. (Zalewski, lecture 2009; Henn, 1996). The question being raised in this particular paradigm is what are the plant and feedback dynamics for patients with BVL? Are they similar to those who have intact vestibular systems? If so could this possibly be the reason why they do have so much trouble with their balance because the “original” plant and feedback dynamics no longer suffice with their new lack of vestibular information. It has also been suggested that these patients may lack the proper feed-forward ability with

the lack of the vestibular system (Fitzpatrick et al., 1996). Could this then be seen in the dynamics of the plant? Creath et al. (2008) saw a possible legs leading strategy in patients with BVL suggesting that they may come up with a new way to maintain balance relying more on the somatosensory information coming from their legs to keep them upright.

It is hypothesized that patients with BVL may use different control strategies to stay upright as compared to healthy control subjects as was seen by Creath et al (2008). This legs leading strategy that may be seen in the phase plots of the patients with BVL may be an indicator of a heavy reliance on the somatosensory information of the legs. It will also be hypothesized that loss of the vestibular system will cause a change in both the plant and feedback components of these patients. With this in mind the medical history as well as extent of any possible vestibular rehabilitation may be reason for varying results between subjects with BVL so it is possible that results will have to be interpreted on a subject by subject basis. It is also hypothesized that the trunk and leg segments will move out of phase earlier than controls as patients with BVL have been known to over rely on the hip strategy for upright stance (Horak & Shupert, 1994).

## **Method**

*BVL Subjects:* All bilateral vestibular loss subjects were recruited from contact information from prior studies, through advertisement on online vestibular forums, through fliers given to doctors, physical therapists and ENTs and through word of mouth. The age cut off for subjects was 55 (Peterka & Black, 1990). The age cut off is due to findings that beyond the age of 55 people *can* begin to sway more due to age alone

(Baloh et al, 1994) but due to the rarity of these subjects it may be necessary to collect data from subjects with BVL slightly over the age of 55. All subjects were required to be able to stand quietly for at least 5 minutes on their own; have no visual problems that can not be corrected with glasses or contacts; VOR gains below 0.1 bilaterally with step responses; electronystagmographic verification of <5 deg/s peak velocity for any irrigation; pendular falls in sensory organization posturography testing; no presence of diagnosed/undiagnosed somatosensory loss in the feet and hands (120 Hz tuning fork); and have no signs of any neurological disorders as determined by their general practitioners. Etiologies include ototoxic drugs, nerve sections, post labyrinthitis as well as idiopathic and autoimmune conditions (Hess, K., 1996). Due to the lack of rotating chair tests available to subjects no patient with BVL was rejected due to only have caloric results, but the other examinations were weighted much more heavily (such as posturography) to ensure that they do have bilateral vestibular loss or at least a very severe hypofunction.

*Control subjects:* Age, gender and weight matched controls were used to compare results. Criteria for selecting healthy subjects include good health status as determined by medical history to eliminate subjects with health problems (cardiac, neurological, balance, psychological, orthopedic, and muscular) and those taking medications that could affect posture and movement control. Control subjects were also required to have had no prior vestibular problems of any nature.

*Equipment:* EMG data was collected from 12 muscles with each subject: soleus, gastrocnemius medialis, gastrocnemius lateralis, tibialis anterior, rectus femoris, biceps femoris, semitendinosus, vastus lateralis, vastus medialis, erector spinae, rectus abdominus and neck extensors. Infrared kinematic makers (Optotrak Inc) were placed on the subject's right ankle, knee, hip and shoulder and on the motors. Two linear motors (Parker Hann, Corp) were used to provide a mechanical perturbation to the subject with a spring attached to a belt, one at the shoulder and one at the waist. Visual perturbations were applied with a random array of computer generated triangles to simulate a wall that will rotate around the ankle within a virtual reality cave. The visual and motor perturbations will consist of a filtered white noise signal. All data processing, signal creation and analysis will be done in Matlab.

*Signals used:* All signals used for the visual and mechanical perturbations were created in MatLab. All signals were filtered white noise signals with different parameters to ensure the proper strength of each perturbation. All perturbations were controlled through Labview 7.2. The parameters are described in the following table for all three perturbations. The shoulder motor had a shorter peak to peak with the hopes that with a shorter distance to travel, the perturbation would have more of an effect.

<b>Perturbation</b>	<b>P</b>	<b>F1</b>	<b>F2</b>	<b>Peak-to Peak Magnitude</b>	<b>Spring constant</b>
<b>Visual</b>	45	0.02 Hz	5 Hz	-5V – 5V	NA
<b>Waist Motor</b>	4	0.6 Hz	5 Hz	13-15cm	0.04 N/mm
<b>Shoulder Motor</b>	2.5	0.8 Hz	5 Hz	11.5-13.5	0.0157 N/mm

**Table 3.1.** Perturbation parameters. Parameters for creating all three perturbation's filtered white noise signals in MatLab. P = power for white noise signal, F1= first cutoff frequency, F2= second cutoff frequency, Peak to Peak magnitude= limit on distance that each perturbation could travel. The visual display is limited to a -5 to 5 volt range and anything beyond those limits is cut off. Motors had a maximum travel distance of 20 cm that could not be exceeded or the motors would shut off.

*Procedures:* Subjects were contacted by the recruiter and a testing date was scheduled.

The subjects transported themselves to the lab the morning of the test date. All subjects arrived at the Cognitive Motor Neuroscience Lab at 8:15 am. The reason for early morning testing was to prevent any fatigue from daily life activities that could have an effect on the already unstable posture of the patients with BVL. Upon arrival the subjects were greeted and given a brief tour of the lab to set them at ease about the events that would be taking place that morning. Once the tour was completed the subjects had the consent forms read and explained to them in detail, which were approved by the Institutional Review Board at the University of Maryland at College Park. When all consent forms were signed and the subject understood what would be done the

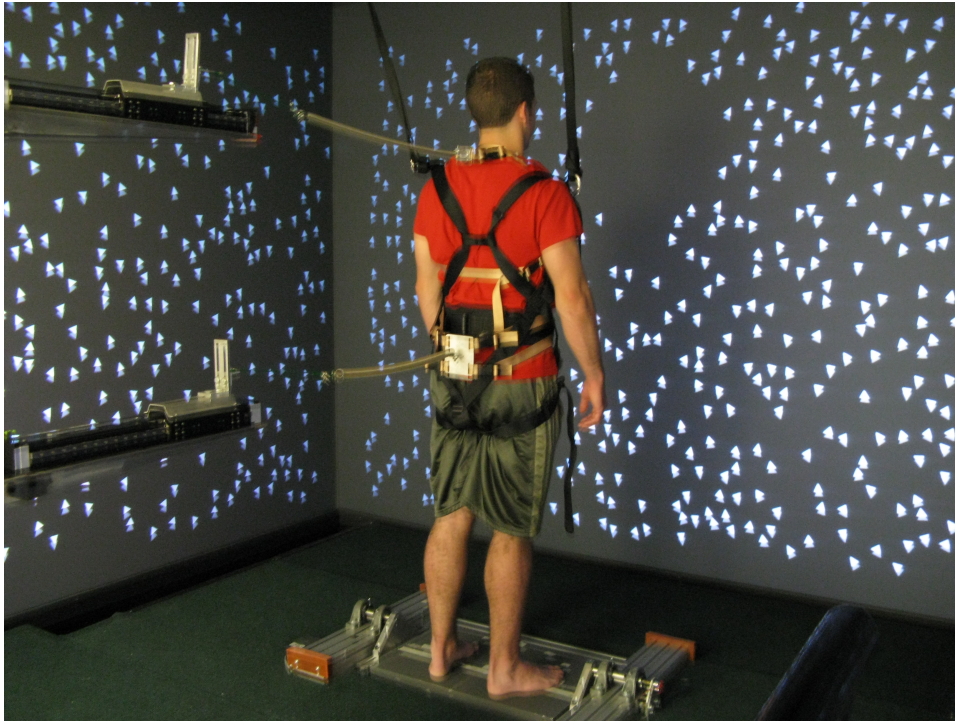


preliminary medical assessments began. All subjects were tested for any signs of peripheral neuropathy using the Semmes Weinstein filament examination as well as tested using a tuning fork of 128 HZ. Any signs of severe sensory loss in the feet automatically disqualified the subject as they needed to be able to have sensation in the lower limbs to be certain that only a lack of the vestibular input is present.

All subjects were walked into the virtual reality cave of the Cognitive Motor Neuroscience Lab after they changed into shorts and short sleeve shirts, which they were instructed to bring for testing. All hair at the site of placement for EMG electrodes was removed to ensure the proper adhesion to the subject's skin. EMG electrodes were placed on the 12 muscles that were described in the above "equipment" section. Once all electrodes had been applied the subject was strapped into a full body harness. The purpose of the harness was to provide protection during the trials. The ceiling of the virtual reality cave has secured straps that when hooked to the full body harness prevent a subject from falling if they feel they are losing their balance. Each subject had the harness adjusted to fit them individually so that the harness did not restrict any sway that was going to be invoked by the perturbations but will was tight enough that if they swayed beyond their stability of support that they would not fall.

All kinematic markers were then placed on the appropriate areas of the subject being sure that no wires crossed any of the EMG electrodes to prevent any possible "cross-talk" during data collection. The waist belt and shoulder belt were then strapped onto the subject at this time. The waist belt is a generic "tumbling" belt that can be found from any gymnastic athletic store and the shoulder belt has been constructed from a collar bone harness that would be given to patients who had normally broken their collar bones.

When constructing these belts the key component was to make sure there was a point of contact for the waist motor spring on the waist belt and a point of contact for the shoulder motor spring on the shoulder belt that when pulled by the springs would effect the entire waist or shoulder and not have a tendency to the pull the subject to one side over the other.



**Figure 3.1- Complete set up for experiment. The shoulder and waist motors have been attached to the subject at the shoulder and waist belts respectively. The two black ropes hanging from above hook to the body harness to prevent any falls**

With this completed the subject was carefully walked up onto the platform into the virtual reality cave over to a seat by the area of the platform where they would be standing. All lights were then turned off and the subject had a few moments to adjust to the lighting of the room, especially since patients with BVL have a harder time moving around in the dark. Subjects were given instructions on how the calibration trials as well as the experimental trials would be conducted for the first time.

When the subject felt they had adjusted to the lighting they carefully were walked up to the designated standing area for the experiment. The calibration trials were executed first. The harness was not attached for these trials so as not to limit their sway since the purpose of the calibration is to measure the full movement about their ankle and hip joints. As the calibration trial began the subjects walked through each step of the trial with the following instructions:

“We are first going to collect data that will allow us to measure how far you can comfortably lean about your ankle joints in the forward and backward direction. When I say the word ‘go’ you will lean forward as far as you comfortably can forward and hold that position for a count of 5. I will count out loud to 5 for you. When that is complete you will move back into an upright position, which we will refer to as the ‘neutral position’ and we will hold that again for a count of 5 seconds, which I will count out loud for you. Upon completion of this you will then lean back about the ankle joint as far as you comfortably can, and this will not be as far as when you were leaning forward, and hold this position for a count of 5. Once that is complete we will move back to the neutral position. This will be considered one cycle and we will complete 3 of these cycles for this part of the calibration. Do you understand?”

If the subject understood then this part of the calibration was started. The subject was walked through every step even after instructions were given. Upon completion of the 3 cycles the same thing was done but with the subject bending only around the hip. The same instructions were given but movement was now about the hip.

When the calibration trials were completed, the subject was hooked to the harness. The spring for the waist motor was attached to a waist belt and the spring for the

shoulder motor was attached to the shoulder belt. The subject was warned that initially the pull of the springs would seem to pull them back but that they would adjust to it in a few moments. The subjects were told to stand in a comfortable, upright position. Before the initiation of the first experimental trial all subjects had their feet positioned shoulder width apart with their toes fanned out 5°. They were instructed to either keep their arms folded across their chests or gently held in front of them. Either position was fine but which ever position they picked they must continue to use throughout the experiment. The subject was also instructed to look straight ahead and try not to look anywhere else around the room. A black spot was located at the eye height of each subject (eye height, as well as ankle height for proper visual perturbation calibration, will have been taken earlier) and this is where they were be instructed to keep their gaze. Once all equipment was properly working and all kinematic markers were seen by the Optotrak camera the first experimental trial commenced. One experimenter always stood behind and to the left of the subject for further safety precaution. Before the commencement of the first trial the following instructions were given:

“We are ready to begin the first experimental trial. Remember that your job is to stand as still as you can and look forward at all times into the black spot in front of you. There will be no talking at any point during the trial, which will last just under 2 minutes in length. If at any time you need to stop because you feel sick or uncomfortable please inform us right away even if it’s in the middle of the trial and we will stop right away. Someone will always be located right behind you during the trials and you are hooked securely in the harness so you have no fear of falling. We do encourage you to try to

finish the trials but if you do feel sick or need to stop please inform us right away. Are you ready to begin the first trial?"

Once the subject gave consent the following instructions were given:

"We are about to begin. Please keep your hands in front of you at all times, keep your feet flat on the floor and try to stare straight ahead into the black spot. We will begin on the count of 3. One...two...three and GO!" At the sound of the word "Go" the motors and visual perturbation were simultaneously started through Labview and data collection commenced. Subjects were to try to complete 20 trials, with the goal of getting 12-15 good trials, unless the bilateral vestibular loss prevented them. Subjects aimed to complete blocks of five, 110 second trials and then were given a rest of 4 minutes. They were informed that if they felt the need they may take longer breaks as well as take breaks more often if they felt they are getting tired. All trials contained the same condition of both the mechanical and visual perturbation being applied for the full 110 seconds.

Subjects stood on a force platform in the virtual reality cave. Two springs were attached to the subject for respective motor connection, providing gentle perturbations to the subject. The motors moved forward and backward in a random fashion. The visual perturbation consisted of an array of 200 white triangles on a black background, rotating in unison about the subject's ankle.

*Data Processing:* EMG and kinematic data were digitally high-pass filtered using a third order zero-lag Butterworth filter with a 15 Hz cutoff frequency. For each trial an average power spectral density and cross spectral density were processed for the signals and the

kinematic and EMG recordings. Gain, phase and coherence were extracted to determine relationships between the input signals, the EMG and the kinematic responses for the plant and feedback components.

*Statistical Analysis:* From frequency response functions gain and phase calculations were made. Confidence intervals will be calculated to determine if frequency values for gain and phase differ significantly from zero.

#### *Patients with BVL and control medical histories*

BVL patient #1 is a 55 year old female who has been diagnosed with BVL for 1 year (since 2008). The cause is from gentamicin ototoxicity. After conducting a medical history exam prior to testing no other major medical issues were seen aside from any that would typically accompany BVL such as oscillopsia, which she does suffer from. Her caloric results suggest a severe bilateral vestibular loss. Warm, cold and ice calorics were conducted. No results for rotary chair or posturography results were reported. Before experimental testing, a Semmes Weinstein monofilament examination and tuning fork (128 Hz) tests were conducted. Results reported normal sensation in the hands and feet. A foam posturography test was also conducted the morning of the experiment. Patient #1 could not stand on the foam with eyes open so the eyes closed trial while standing on foam was canceled for safety purposes since her abnormal sway with eyes open was indication enough of her severe bilateral loss.

BVL patient #2 has had BVL for 7 years and his cause is unknown though it is thought it may have resulted from some traumatic childhood head injury or possibly a

severe ear infection that he encountered as a child. Caloric results were not available but rotary chair results for frequencies between 0.1 and 0.16 suggested a severe bilateral vestibular loss. Sensory organization test results backed these results as he had abnormal sway for tests 5 and 6 with precipitous free falls.

Both control subjects were age, height and gender matched to their BVL counterparts. Both completed the medical history questionnaire and showed no sign of any major medical disorder (neurological or physiological) and had no history of any form of vestibular disorder. They also both completed the Semmes Weinstein monofilament and tuning fork examinations as well as the foam posturography test prior to the experiment and showed normal results.

Both patients with BVL completed a questionnaire after the experiment to get a more complete idea of their lifestyles both prior to and after their bilateral vestibular loss. Both patients stated they had the ability to still continue to do many self care activities but some day to day activities have become slightly difficult, though not impossible, to accomplish. Both patients also drive during the day. BVL patient #1 reported that she can not be a passenger in a car as it would make her very uncomfortable and must be the driver. When she does drive during the day she uses her Tom-tom device. While driving it can be hard to keep her attention but finds that with the Tom-tom giving her directions it makes it easier to accomplish this task. She does not drive at night. BVL #2 will drive at night only if he knows the route as the oscillopsia with the night lights can make driving very difficult for him. He also drives himself to work but feels that one reason he does this is because he does not have a very taxing commute and felt that if he had to

work in a congested city, such as New York City, that it may be too impossible because of all the visual stimuli.

BVL patient #1 no longer works since the onset of this disorder but when she did work she was at IBM for 32 years. BVL #2 does continue to work as a technical manager. He sits at a desk to do data analysis and writes reports. He states that because of the low amount of physical activity required by his job he is able to continue to work. BVL patient #1 has trouble watching TV and reading and has even a harder time trying to shop. She tries to make any sort of outings at times when there will be as few people as possible in the store as too much movement and activity going around her becomes frighteningly overwhelming. BVL #2 does not have trouble watching TV or reading, unless he is moving or bouncing in a vehicle as these would instigate his oscillopsia. He does continue to shop but finds the lighting can make things a little annoying when trying to get around. BVL #1 can use a computer for a little while but does not need to take breaks. BVL #2 has no issue using a computer. As far as ambulating in public places, BVL #1 can only go up anything with two or less steps. Anything more then that becomes impossible. She also states that she can not walk on grass without compromising her stability. BVL #2 can go up stairs and ramps provided there is a railing. If the surface he is walking on is irregular he will have more trouble. When escorting him from the lab after the first night of testing his gait changed drastically in the darker environment but he was still able to walk on grass and the pavement but it was noted that he did appear to lift his legs higher. Both patients did attend physical therapy initially after their diagnosis. BVL #1 attended for 6 weeks while BVL #2 attended for 1 month. BVL #1 remembers completing the following activities with her physical



therapist: walking on a treadmill (though she greatly disliked this activity), heel to toe walking, positioning objects with eyes opened and closed, throwing objects from one hand to another while walking, walking and stepping over objects such as shoe boxes, as well as walking sideways and backwards. As BVL #2 had completed his physical therapy a few years ago it was harder for him to recall but he listed many of the same exercises as BVL #1 had. BVL #1 continued these exercises sometimes at home but claims the physical therapy has not helped at all. BVL #2 also continued them at home but did not feel they were helping very much. BVL #2 unlike #1 continued to stay physically active. He was an avid swimmer before the vestibular loss and re-taught himself how to swim. He also continues to run as well as lift weights after the vestibular loss and thinks that having continued these physical activities even after the loss has really helped him compensate. Before the vestibular loss #2 also would hike, surf, play tennis and baseball but finds some of these still hard to do with the vestibular loss. BVL #1 did not report continuing to do any physical activities after the loss. Before her vestibular loss she would boat and camp a lot on the weekends as well as build doll houses. She has tried every so often to build dollhouses again since the BVL but can only handle doing this for a few hours a week. Neither patient has picked up any new activities since the initiation of the BVL.

## CHAPTER IV

### Results

All subjects completed 20 trials (4 blocks of trials with a break in between). The goal was to collect between 12-15 trials of good data after doing the initial analysis. Due to EMG issues BVL #1 only had 10 trials that could be analyzed. Therefore, her control, Control #1 only had 10 trials analyzed. BVL #2 had 15 trials that were available for analysis. Even though there would be 5 trial data difference between the two patients it was determined that since these patients are so variable to begin with that more trials would only help with data interpretation.

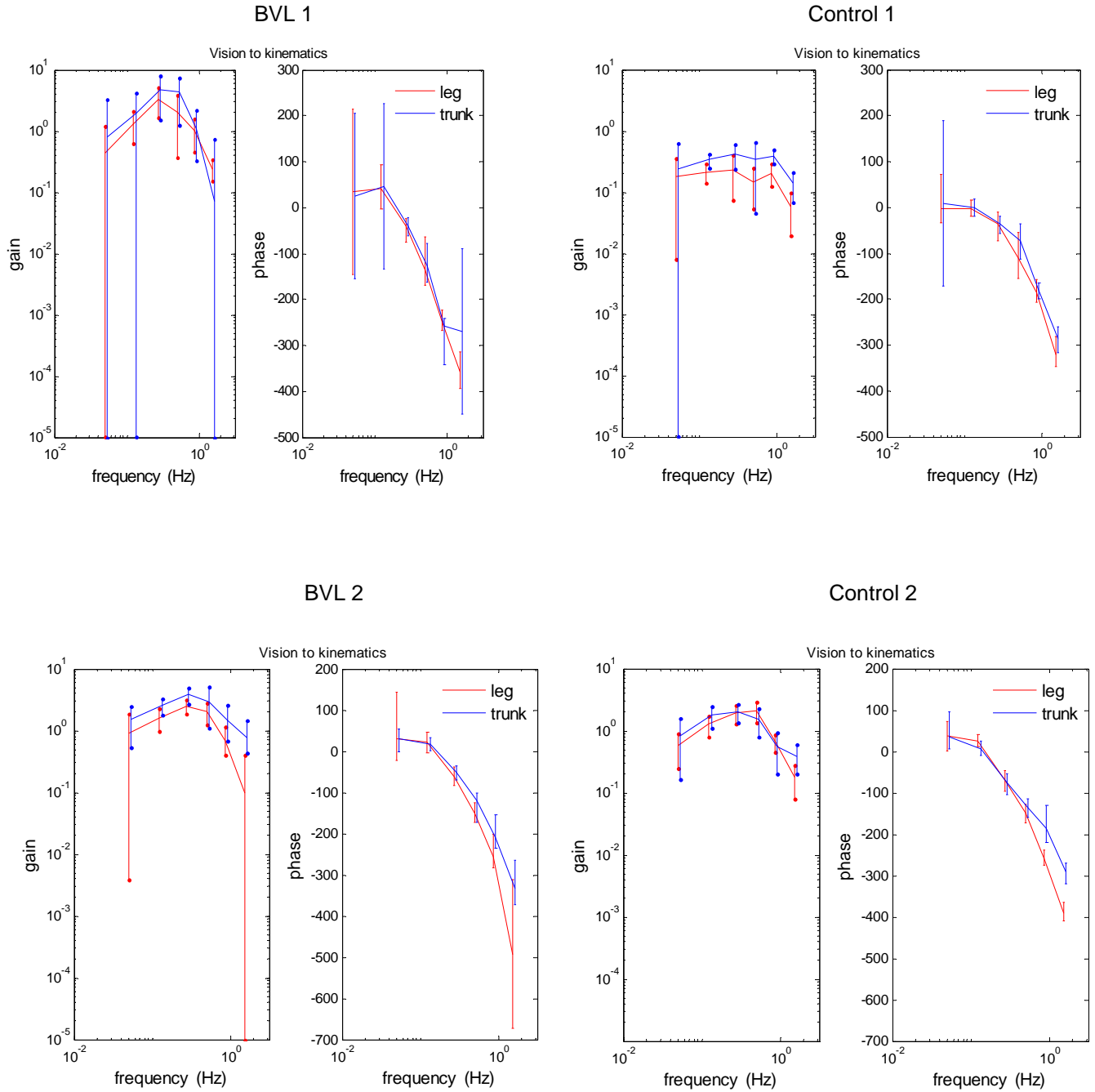
#### *Plant Frequency Response Functions*

##### *Closed Loop FRF from visual perturbation to body segments*

Kinematic gain and phase responses to the filtered white noise visual perturbation are shown in Figure 4.1 for both patients with BVL as well as both controls. Each BVL patient's results are always paired directly to the left of their control counterparts for all of the following figures. BVL patient #1 and Control #1 have data that is averaged across 10 trials for all plots. BVL #2 and Control #2 have data that has been averaged across 15 trials. The reasoning for this is that BVL #1 only had 10 trials that were clean enough to analyze for multiple reasons, requiring control #1 to be averaged across only 10 of her trials to keep things equal. BVL #2 was able to make it through 15 trials, and

since the goal was to get the patients through 12-15 clean trials all 15 were analyzed. His control, Control #2, therefore also had 15 trials analyzed.

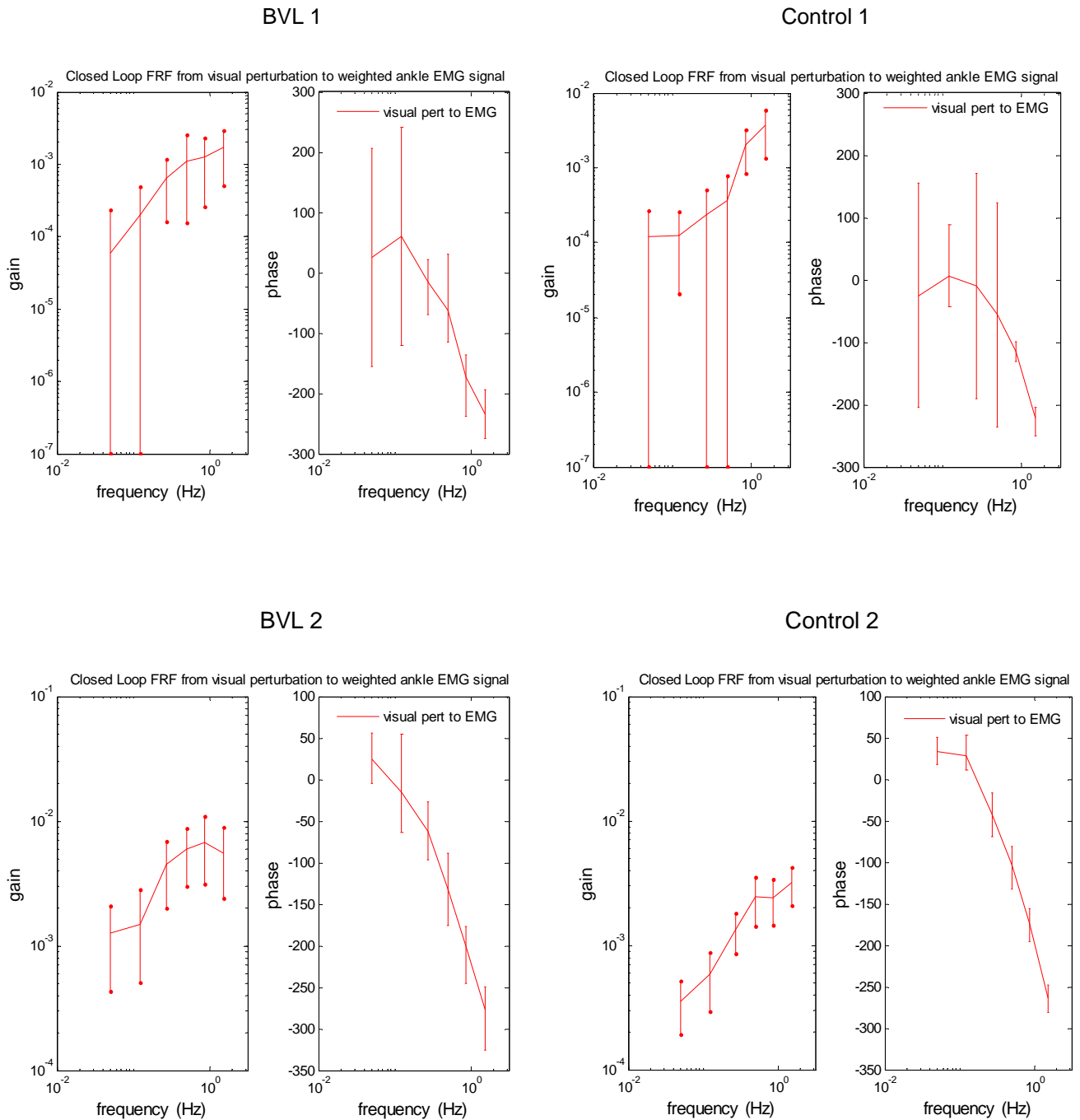
As was expected both patients with BVL showed higher gains in comparison to their controls. BVL #1 shows a greater gain difference compared to her control which could possibly be due to her little compensation in comparison to BVL #2. Control #2 shows a higher gain compared to Control #1, but is still lower than BVL #2 especially when considering the trunk kinematics across all frequencies to the visual perturbation. All four subjects showed a trunk leading pattern to the visual perturbation.



**Figure 4.1** Closed loop vision to kinematics. Vision perturbations to gain and phase for all 4 subjects. Error bars are 95% confidence intervals for each frequency bin. BVL and Control #1 have data averaged across 10 trials as BVL #1 was limited in the number of clean trials she had for numerous reasons. BVL and Control #2 are averaged across 15 trials as the goal of the experiment

*Closed Loop FRF from visual perturbation to weighted EMG*

The following data shows the response of the weighted ankle and weighted hip EMG to the visual perturbation. Weighted ankle data contains the following muscles: soleus, gastrocnemius lateralis, gastrocnemius medialis and tibialis anterior. Weighted hip data contains the following muscles: rectus femoris, vastus lateralis, vastus medialis, bicep femoris, semitendinosus, and rectus abductus. Figure 4.2 shows closed loop FRF data of the visual perturbation to weighted ankle EMG data.

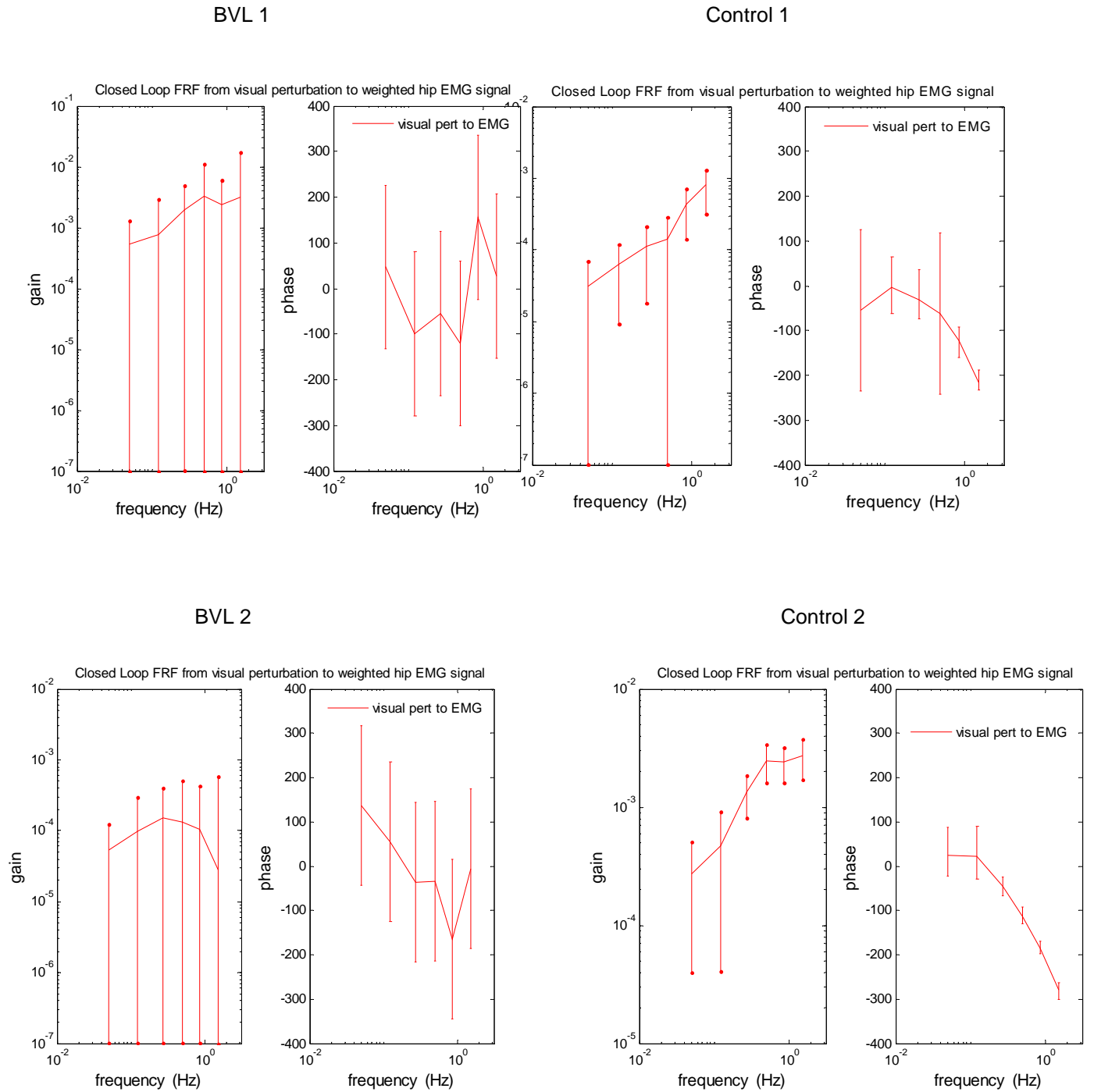


**Figure 4.2** Closed loop visual perturbations to weighted ankle EMG. Figure for all four subjects. Error bars represent 95% confidence intervals for each frequency bin.

Both patients with BVL show higher gains compared to their controls though BVL #1 only shows higher gains at the higher frequencies while BVL #2 shows higher gains across all frequencies. All subjects show in phase patterns of the weighted ankle signal

with respect to the visual perturbation at the low frequencies and slowly become out of phase at the higher frequencies. BVL #2 and Control #2 show cleaner results compared to both BVL #1 and Control #1. A possible gender difference could exist as BVL and Control #2 are both male though more subjects would be needed to confirm this difference statistically. To my knowledge, there is no evidence of gender differences with patients with BVL in the literature.

Figure 4.3 shows weighted hip data for all four subjects to the visual perturbation.



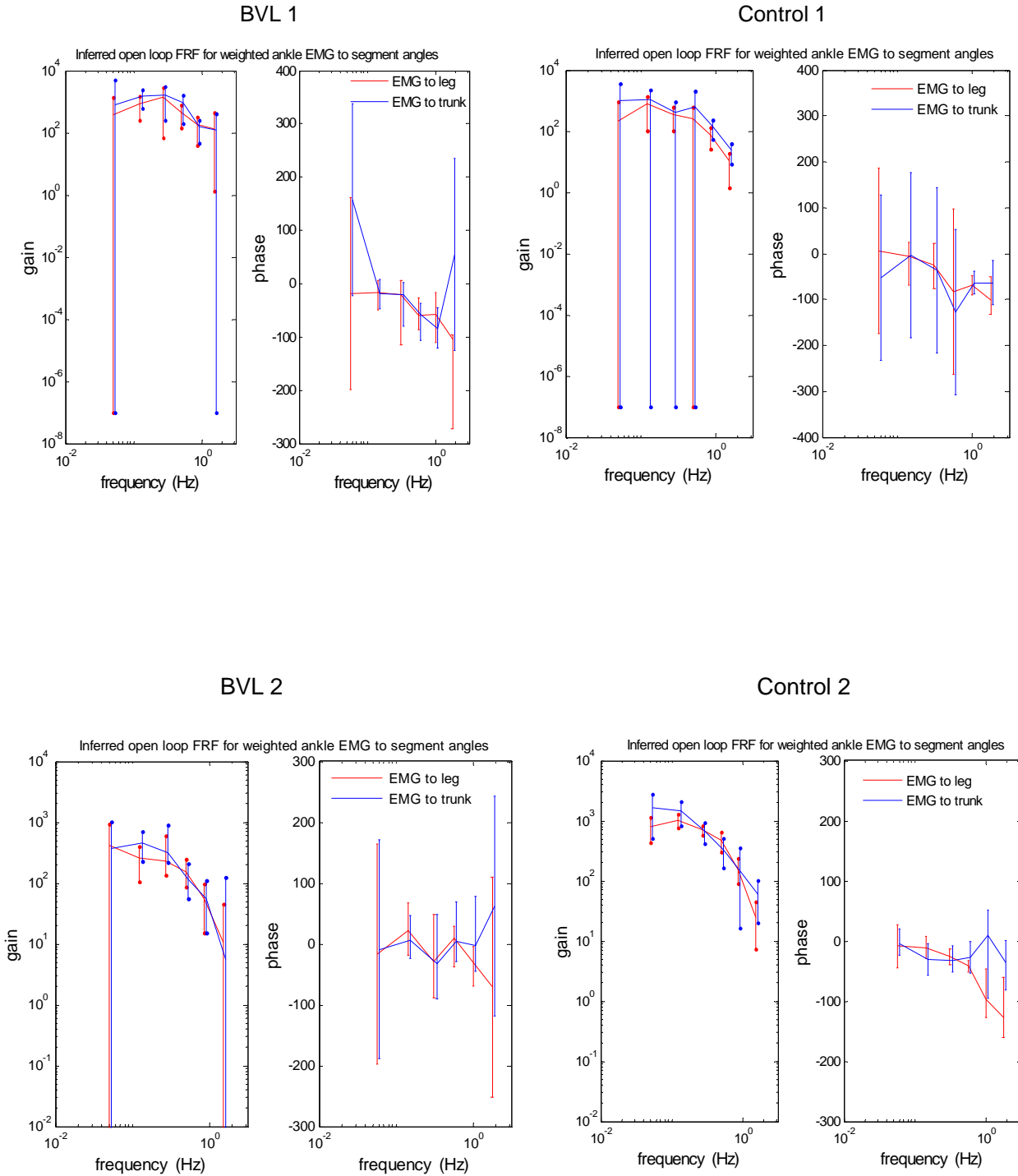
**Figure 4.3** Closed loop visual perturbation to weighted hip EMG. Gain and phase plots for visual perturbation to weighted hip EMG data for all four subjects. Error bars are 95% confidence intervals for each frequency bin.



Data for both controls for weighted hip EMG responses to the visual perturbation is similar and shows significance from zero at all frequency bins. Both controls show increasing gain and decreasing phase with an increase in frequency. Both patients with BVL on the other hand show variable results for both gain and phase as none of the binned frequencies for gain or phase show any significance from zero. This would suggest that both patients were unable to properly control the use of their hips, which is consistent with the literature (Black et al, 1998). When comparing the weighted hip to weighted ankle EMG data, at least for the controls, the hip EMG data appears to lead the weighted ankle EMG data. This comparison is harder to make for the patients with BVL as the data shows no significance from zero at any of the binned frequencies.

#### *Inferred open loop FRF for weighted EMG to segment angles*

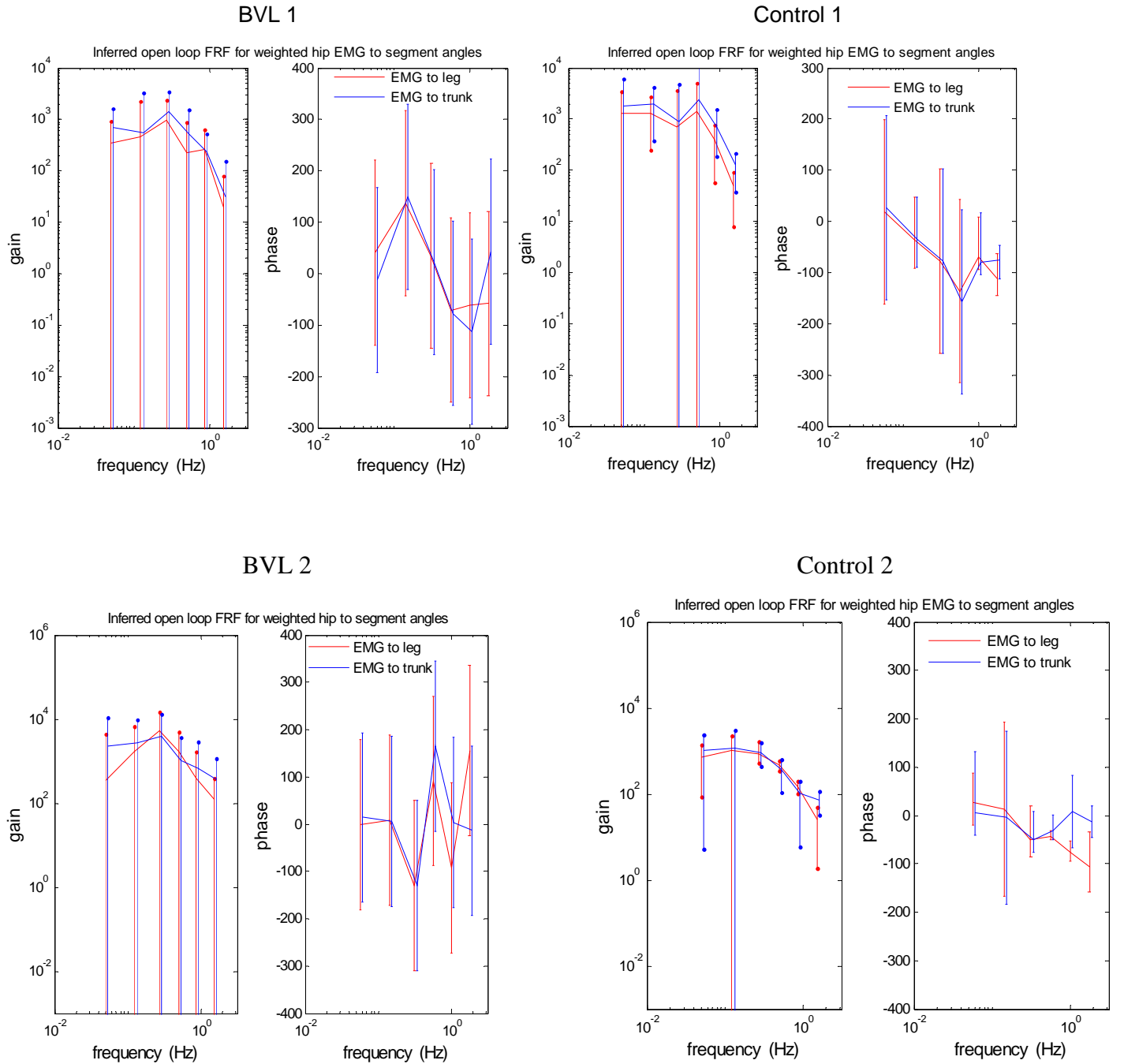
The following figures show inferred open loop data for the weighted ankle and weighted hip EMG to the kinematic segment angles for all four subjects. Figure 4.4 shows data for the inferred open loop for weighted ankle EMG to the body segment angles.



**Figure 4.5** Inferred plant open loop FRF for weighted ankle to leg and trunk kinematics. Gain and phase plots for all four subjects. EMG to leg= leg response to the weighted ankle EMG. EMG to trunk= trunk response to the weighted hip EMG. Error bars indicate 95% confidence intervals for each frequency bin.

Results for BVL and Control #2 appear cleaner than BVL and Control #1. The reasoning for the variable results for Control #1 may be due to her variable weighted ankle EMG data results, which would cause calculation for inferred open loop to be messy as well. All subjects seem to show a legs leading pattern in the phase data at higher frequency bins. Due to the lack of significance from zero for both patients with BVL at the first and last frequency bins, phase does not decrease from an in phase pattern at the low frequencies to an out of phase pattern at higher frequencies as is seen with the controls. The middle frequency bins (bins 2-5) do show some consistency with the pattern that is seen by the controls. Gains start at the same point for all 4 subjects at the low frequencies though BVL #1 show higher gains at higher frequencies in comparison to all the other three subjects, indicating her possible lack of compensation.

Figure 4.5 shows the inferred open loop data for the weighted hip EMG to body segment angles for all four subjects.



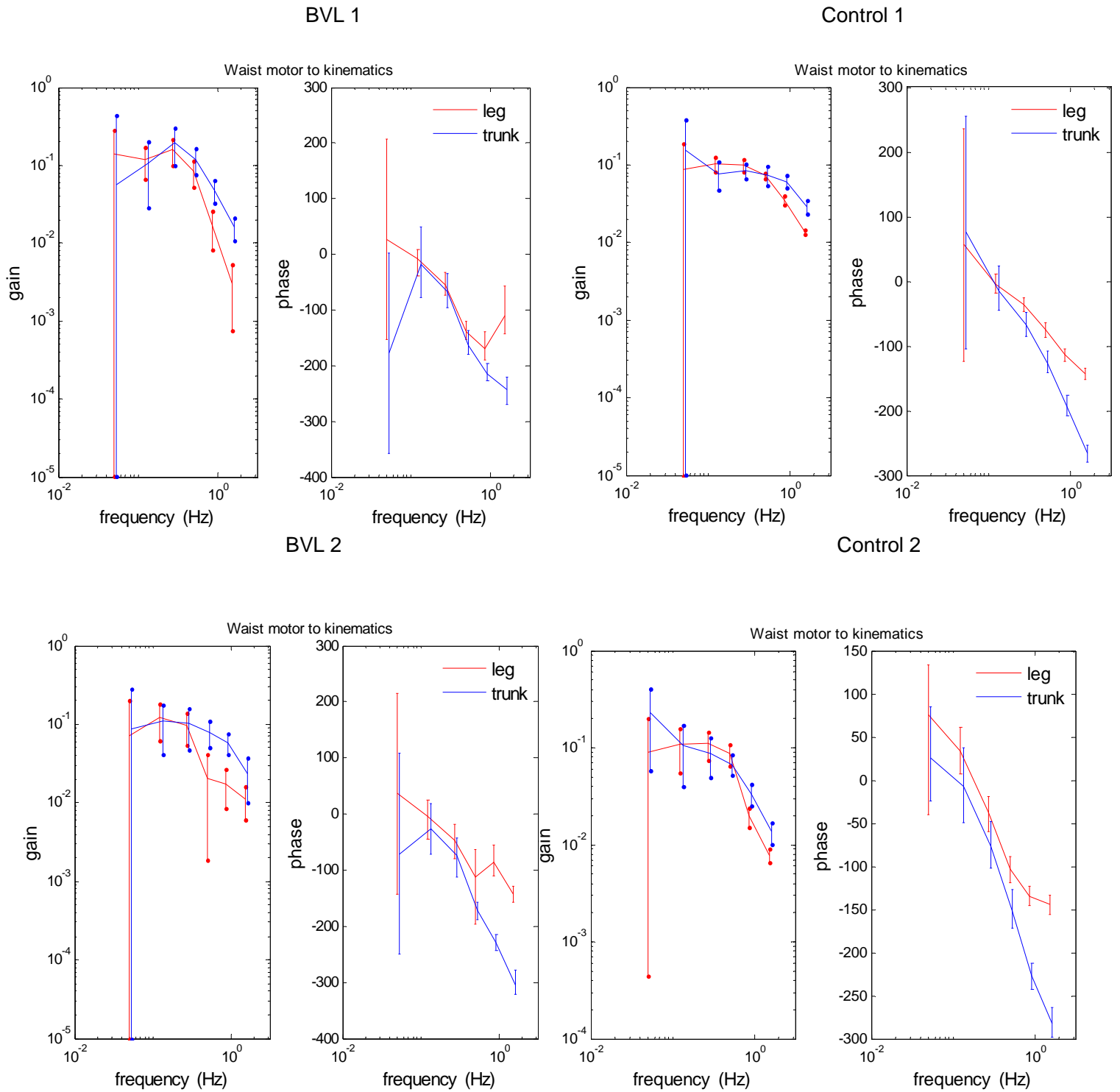
**Figure 4.5** Inferred plant open loop weighted hip EMG to kinematic response. Gain and phase plots for all four subjects. Error bars represent 95% confidence intervals for each frequency bin. EMG to leg = leg kinematic response to weighted hip EMG signal. EMG to trunk = trunk kinematic response to weighted hip EMG signal.

For both controls most frequency bins for gain and phase show significance from zero for both the leg and trunk kinematics. At higher frequencies there appears to be a trunk leading relationship to the leg kinematics for both controls. None of the bins show any significance from zero for both patients with BVL, making it hard to interpret the gain and phase results. The significance here is that both patients show these “messy” results for weighted hip inferred open loop plant data. This further suggests that both of these patients could not properly utilize their hips for postural sway like their control counterparts.

### *Feedback Frequency Response Functions*

#### *Closed loop FRF from waist mechanical perturbation to body segment angles*

Closed loop data is analyzed in the following figures for each individual motor. All signals for both the waist and shoulder were created with a filtered white noise signal. Figure 4.6 is the closed loop waist motor perturbation to kinematic body segment angle response for all four subjects.



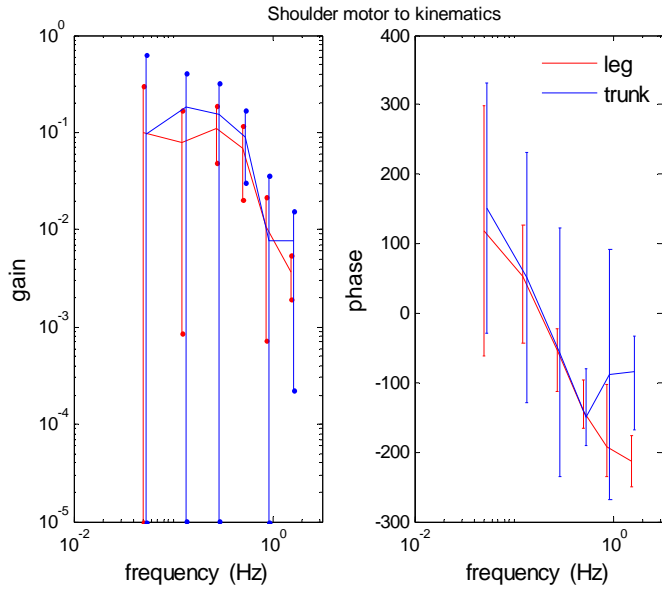
**Figure 4.6** Closed loop waist perturbation to kinematics. Gain and phase plots for all four subjects. All error bars are 95% confidence intervals for each frequency bin.

All four subjects show out of phase patterns at high frequencies and also show a legs leading pattern in their phases for the waist motor perturbation. Both control subjects appear to have a clear separation of both the leg and trunk kinematics across the frequency bins. BVL #1 shows the least amount of separation and moves her leg and trunk in phase with each other. This is supported by the belief that patients with BVL attempt to align all body segments in-phase as a simple control strategy to remain upright (Black et al, 1988). BVL #2 appears to show a leg-trunk phase pattern that is between the controls and BVL #1, possibly showing his ability to have compensated since being diagnosed with bilateral vestibular loss.

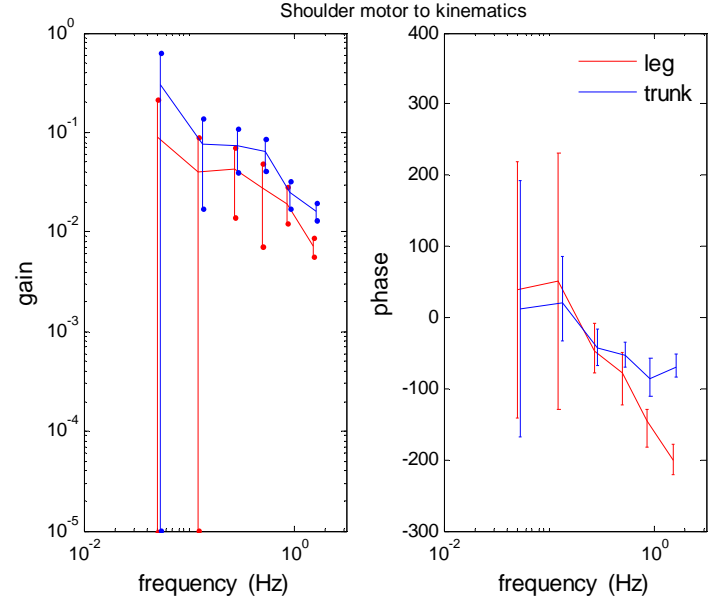
Figure 4.7 shows the closed loop feedback data for the shoulder motor to kinematics for all four subjects.



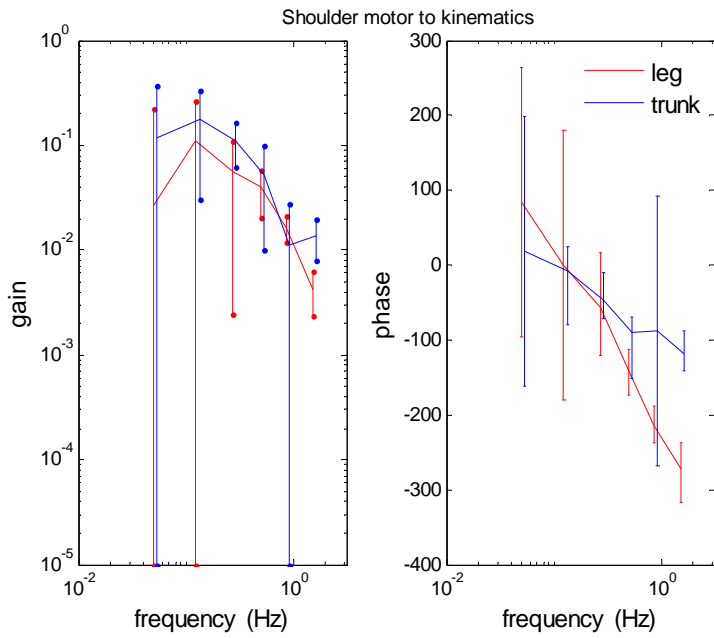
BVL 1



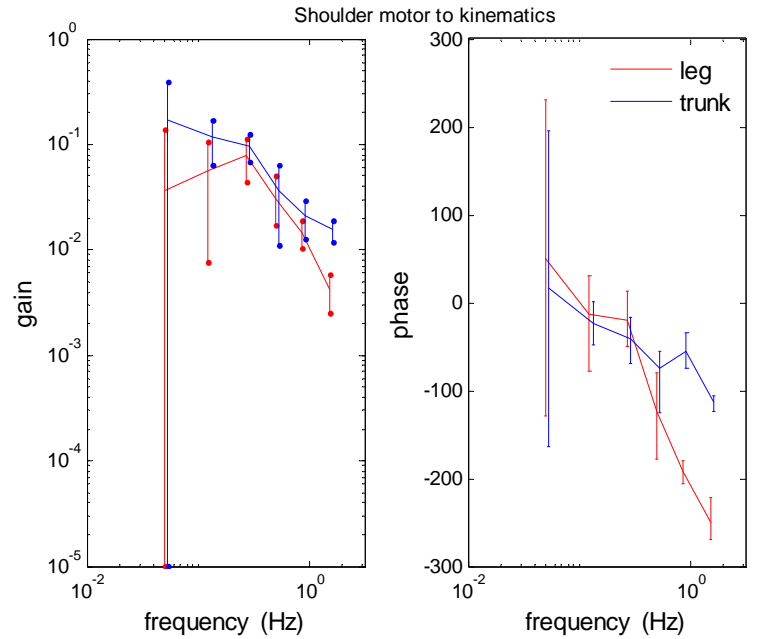
Control 1



BVL 2



Control 2

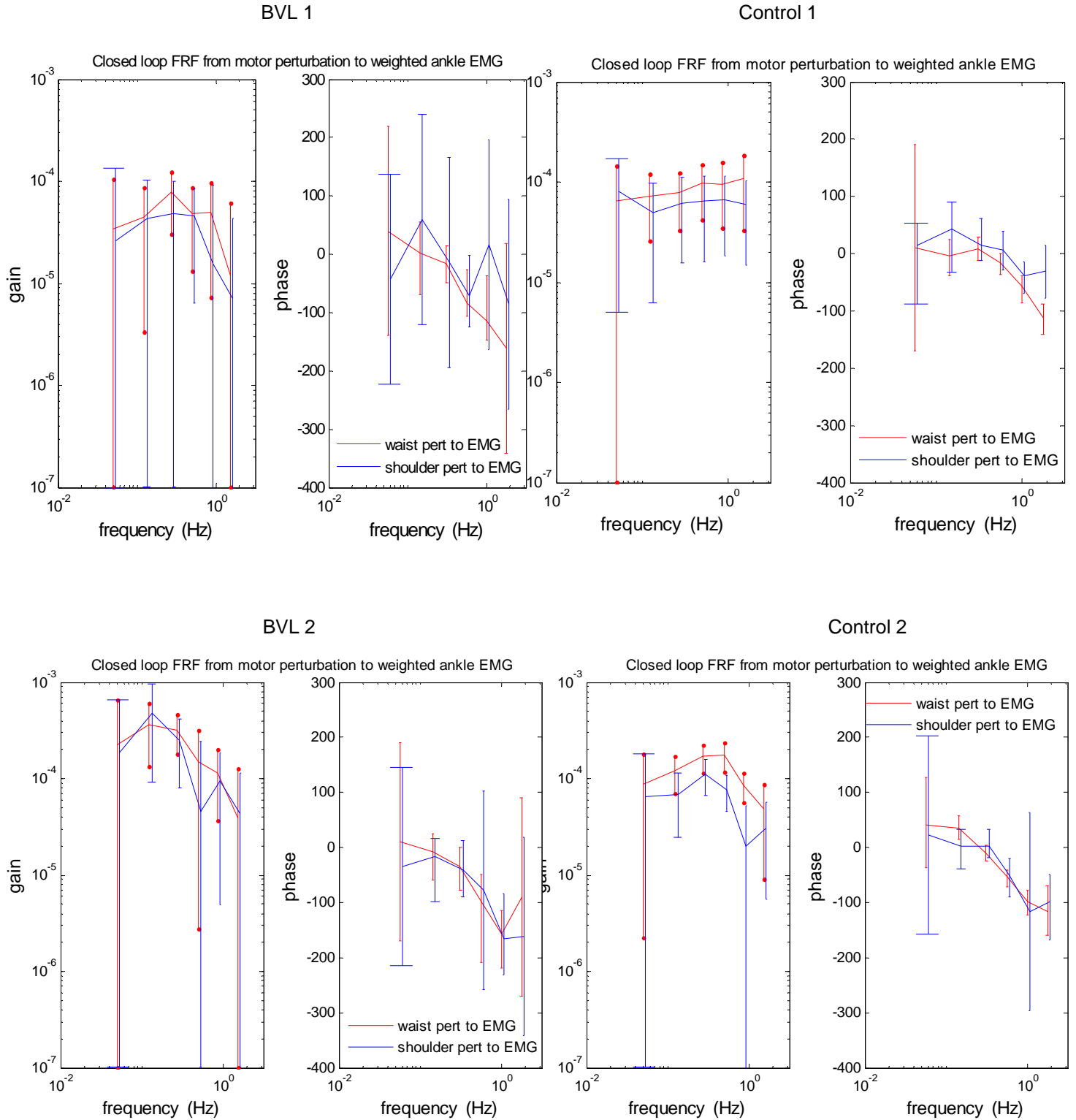


**Figure 4.7** Closed loop shoulder motor to kinematics. Gain and phase plots for all four subjects for shoulder motor perturbations to kinematics. Error bars are 95% confidence intervals for each frequency bin.

All four subjects show a trunk-leading-legs phase relationship at higher frequencies. As was seen in Figure 4.6 BVL #1 is again showing a pattern where both the legs and trunk are in phase with each other across frequency bins. This may suggest her inability to maintain upright stance with different phase relationships of the legs and trunk, unlike BVL #2 and both controls. Less significance from zero is indicated by the error bars across all subjects. This is more apparent for the patients with BVL.

*Closed Loop FRF from mechanical perturbation to weighted EMG*

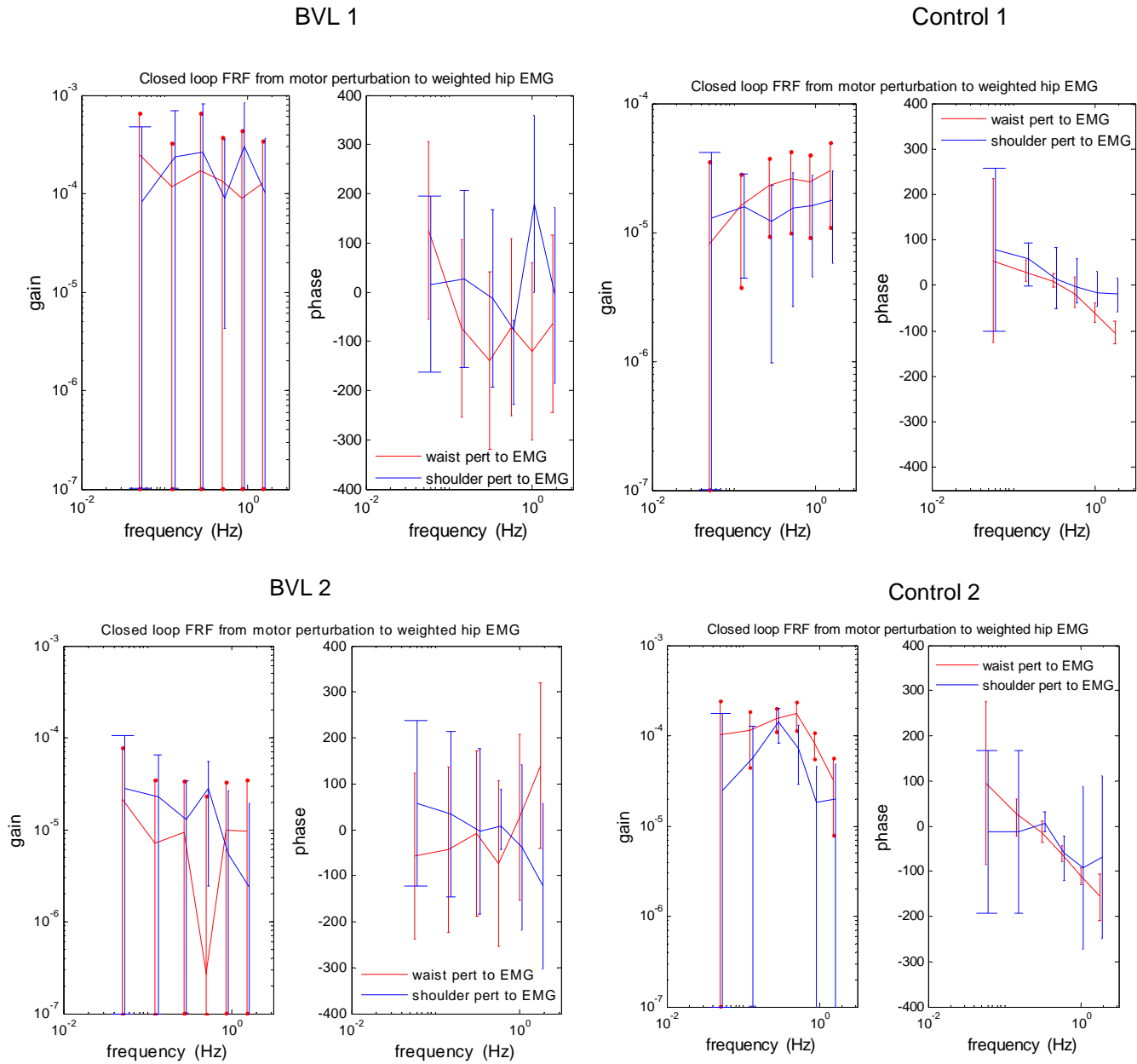
The following plots are for the waist and shoulder perturbations (separately) to both the weighted ankle EMG data as well as for the weighted hip EMG data. Figure 4.8 shows the weighted ankle data for all four subjects to the waist perturbation.



**Figure 4.8** Closed loop motor perturbation to weighted ankle EMG. Gain and phase plots for all four subjects. Error bars represent 95% confidence intervals for each frequency bin. Waist pert to EMG= waist perturbation and its effect the weighted ankle EMG response. Shoulder pert response= shoulder perturbation and its effect on the weighted ankle

For BVL #1 weighted ankle EMG data is much more variable for the shoulder perturbation as compared to the waist perturbation. BVL #1 also has the largest amount of variability suggested by the fact that most of the error bars show a lack of significance from zero. BVL #2 appears to show a legs leading pattern unlike the other three subjects at the highest frequency bins.

Figure 4.9 shows gain and phase plots of the FRF for the mechanical perturbations to weighted hip EMG.



**Figure 4.9** Closed loop motor perturbation to weighted hip EMG. Gain and phase plots for all four subject for mechanical perturbations to weighted hip EMG. Error bars are 95% confidence intervals for each frequency bin. Waist pert to EMG= waist perturbation and its effect on the weighted ankle EMG response. Shoulder pert response= shoulder perturbation and its effect on the weighted ankle EMG response.

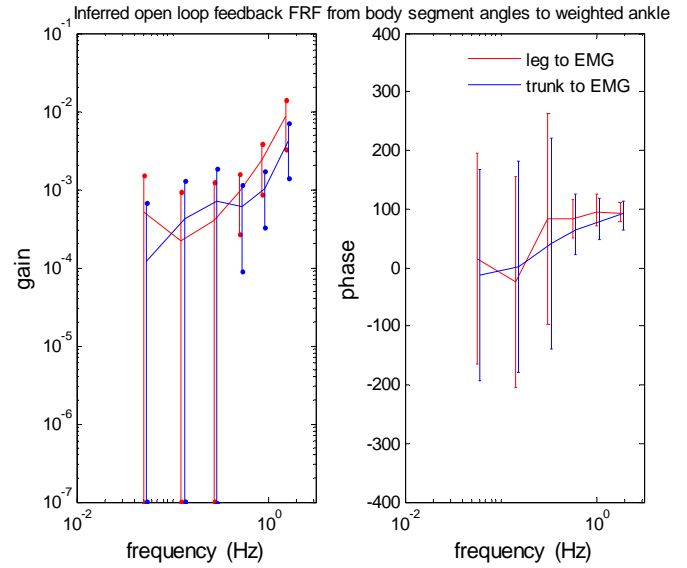
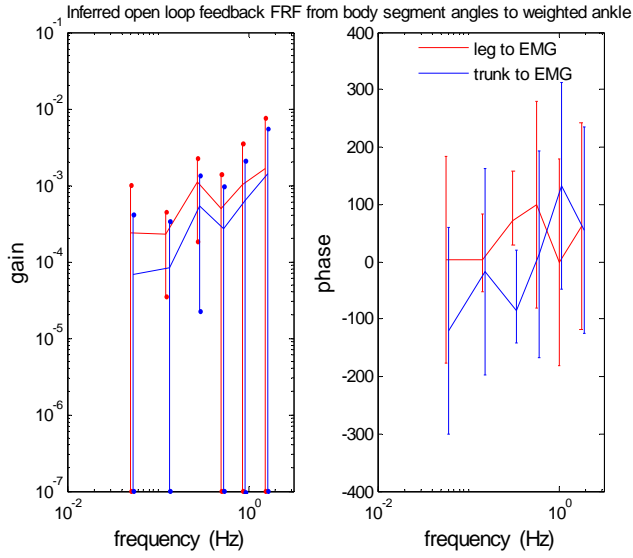
All four subjects show less significance from zero with the weighted hip EMG data to both perturbations. The patients with BVL both show the least amount of data points that are significantly different from zero. Phase patterns are very hard to determine for both patients for this reason. Both control subjects show more consistent responses, indicated by smaller confidence intervals. This difference between the patients with BVL and the controls again suggests that these patients have a very difficult time controlling their hips to maintain upright posture.

*Inferred Open Loop feedback FRF from body segment angles to weighted EMG*

The following plots depict data for inferred open loop feedback FRF from body segment angles to weighted EMG for all four subjects. Figure 4.10 shows inferred open loop feedback FRF for all four subjects to weighted ankle EMG data.

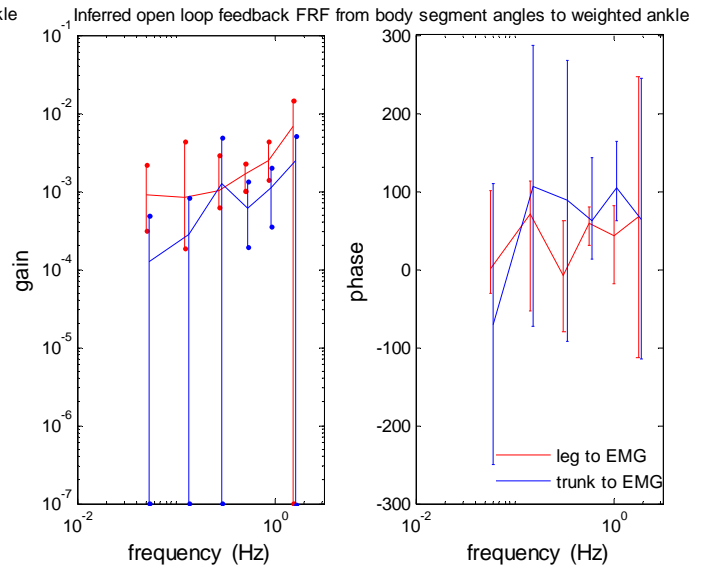
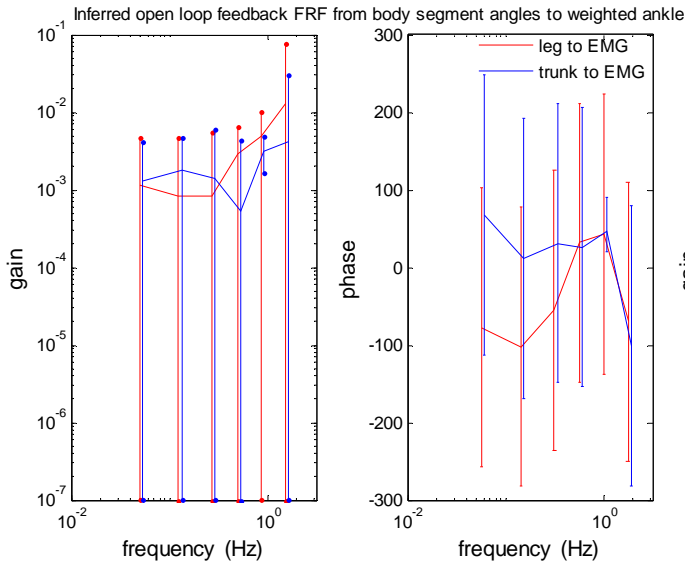
BVL 1

Control 1



BVL 2

Control 2



**Figure 4.10** Inferred open loop body segment angles to weighted ankle EMG. Gain and phase plots for all four subjects for inferred feedback open loop FRF for body segment angles to weighted ankle EMG signal. Error bars 95% confidence intervals for each frequency bin.

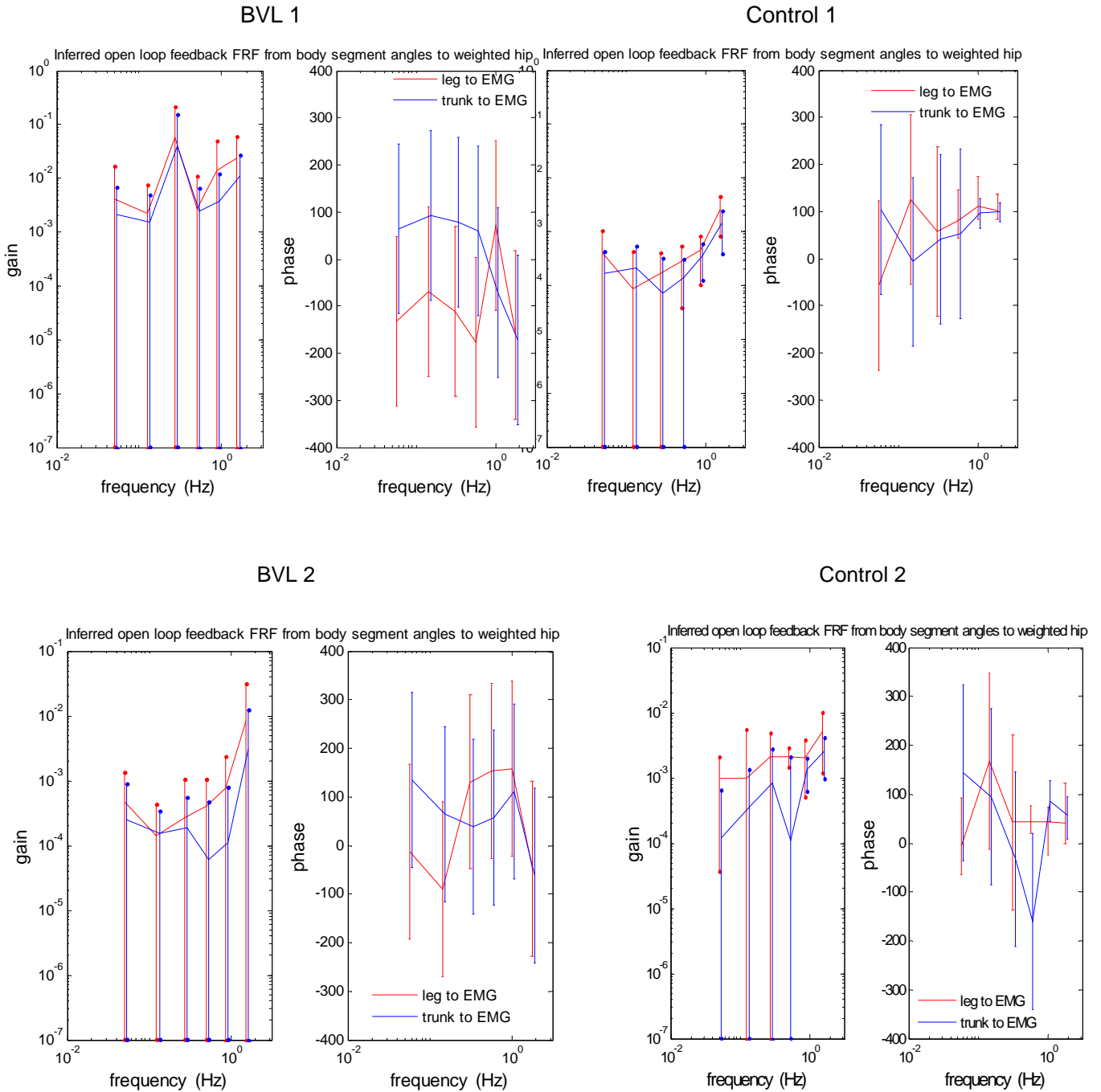
Leg to EMG = leg kinematic segment to weighted ankle EMG signal response.

Trunk to EMG = trunk kinematic segment to weighted ankle EMG signal response.

All four subjects show reduced significance from zero for gain and phase. Both BVL subjects show more variable phase data in comparison to their control counterparts as well as less significance from zero. Both patients with BVL show a phase separation of the trunk and leg segments at the lower frequencies but BVL #1 shows a legs-leading-trunk pattern while BVL #2 shows a trunk-leading-legs pattern, although the responses are highly variable and difficult to discern.



Figure 4.11 shows inferred open loop data for the mechanical perturbations to weighted hip EMG data for all four subjects.



**Figure 4.11** Inferred open loop body segment angles to weighted hip EMG. Gain and phase plots for all four subjects for inferred feedback open loop FRF of body segment angles to weighted hip EMG. Error bars indicate 95% confidence intervals for each frequency bin. Leg to EMG = leg kinematic segment to weighted ankle EMG signal response. Trunk to EMG = trunk kinematic segment to weighted ankle EMG signal response.

Data again is variable for all subjects, though the patients with BVL show the least amount of significance from zero according to the 95% confidence intervals. This lack of significance, which again is more apparent for the weighted hip data than the weighted ankle supports the idea that patients with BVL have a harder time controlling their trunk movements.

# Chapter V

## Discussion

### *Plant Frequency Response Functions*

#### *Closed Loop FRF from visual perturbation to body segments*

Control subject responses for the visual perturbation to the kinematic segments both showed fairly similar results in Figure 4.1. At higher frequencies the trunk appeared to lead the leg segments in the phase plots. Both controls had similar gain patterns though the gains for Control #2 were higher than for Control #1. This could be for a few reasons. Control #2 may be heavily reliant on visual information compared to Control #1. Control #2 was also much higher than Control #1. There is a possibility that the height had an influence.

As was expected from the patients with BVL both showed a higher gain to vision compared to their controls (Peterka, 2002). This was very apparent when comparing BVL #1 to her control. Both subjects start a little below a gain value of  $10^0$  but as frequency increased BVL #1 had gains that continued to soar close to  $10^1$ , especially for the trunk segment, unlike Control #1 who had gains that stayed relatively the same and dropped slightly at the highest frequency bin. This supports what was found by Peterka in 2002, that the patients with BVL are very visually dependent. BVL #2, still seemed to have higher gains than his control at the higher frequencies for the trunk segment. When comparing both patients with BVL, BVL #1 has much higher visual gains, except at the highest frequency bin though the lack of significance from zero for that bin makes it hard to determine. This could be due to her lack of adaptation. Having only had BVL for a

year while #2 has had it for 7 years may show that time for adaptation can make these patients less dependent on visual information. BVL #2 has also stayed involved in many physical activities while BVL #1 has not. This could suggest that staying physically active, even with the difficulty that this bilateral loss can bring, is very important for allowing these patients to adapt. Creath et al (2008) suggests that the vestibulospinal tract normally would help maintain trunk stability and therefore the lack of this tract with this patient population may be the reason for their bigger trunk movements. All subjects have a trunk leading pattern when compared to the legs in the phase plots.

#### *Closed Loop FRF from visual perturbation to weighted ankle EMG*

Controls show similar phase and gain patterns in Figure 4.2. The ankle EMG starts in phase with the visual perturbation at lower frequencies and then decreases with increasing frequency. Gain increases with increasing frequency.

Both BVL subjects appear to have higher gains for their ankle EMG to vision compared to their controls. This would also be expected as the patients with BVL are visually dependent.

#### *Closed Loop FRF vision to hip EMG*

Again both controls seem to show similar gain and phase patterns in Figure 4.3. Hip EMG gains appear to be lower than ankle EMG patterns when comparing Figures 4.2 and 4.3 for the controls. This is true especially for the lower frequencies but the difference between the ankle and hip gains at the higher frequencies becomes smaller. This could be because at smaller frequencies for the visual perturbation the controls only

need to apply movement about the ankle but as the frequencies increase the controls need to incorporate more movement at the hips to stay upright.

The patients with BVL on the other hand have no data points for gain with the hip EMG that are statistically significant from zero. This makes the phases for both of these patients hard to interpret. It is believed that patients with BVL have trouble controlling their hip movements, either because they physically can not do it with the lack of vestibular input or they will not move about the hip because consciously these patients know it will throw them off balance (Black et al, 1988). The fact that the ankle EMG has much more significance and cleaner gain and phase patterns compared to the weighted hip EMG would also suggest that these patients had a tough time utilizing their hip muscles accurately, if at all.

When studying the trends of the weighted hip EMG gain to the weighted ankle EMG gain for both BVL subjects it is interesting to note that BVL #1 has a higher weighted hip EMG gain than her weighted ankle gain to the visual perturbation while BVL #2 is the opposite. It is possible that BVL #1's lack of compensation could be causing her trunk to follow the visual perturbation. Her matched control shows a weighted hip EMG that is much lower than hers across the frequency bins. BVL #2 on the other hand shows weighted hip EMG gains that are consistently lower than his control's gains. When speaking to BVL #2 before testing he mentioned that when he does posturography tests or is moving around in his day to day life he pays attention to the information he gets from his feet and legs to keep him upright. He stated that during swaying platform tests he would always use his feet to let him know where he is with

respect to the platform. It is possible that he is in some way acting to keep his trunk from linking to the visual environment.

*Inferred open loop FRF for weighted ankle EMG to segment angles*

In Figure 4.4 Control #1 has less binned data points at the low frequencies that are significantly different from zero. This could possibly be due to the calculations for inferred open loop as any messy EMG or kinematic closed loop data would influence the significance found for the inferred open loop. Both controls show a trunk leading pattern at higher frequencies.

Similar gain and phase patterns are seen between both patients with BVL as well as between the patients with BVL and their controls. Due to the lack of significance for both the first and last bins for EMG to leg and trunk for both patients its hard to determine with certainty whether their plant shows a trunk leading strategy but the pattern would at least suggest that it is possible. All four subjects start with both kinematic segments being in phase with respect to the weighted ankle EMG signal and then growing out of phase at the higher frequency bins.

*Inferred open loop FRF for weighted hip EMG to segment angles*

Both controls show similar gain and phase trends in Figure 4.5 with gains slowly decreasing as frequency increased. Both also seem to show a trunk leading pattern, though Control #2 shows this more than Control #1.

Both patients with BVL have data that can not be interpreted due to the lack of significance. Once again this strong lack of significance is seen with regards to the

weighted hip EMG. When interpreting this with respect to the plant for this population these patients may be unable to properly create a proper weighted hip EMG signal. Interestingly even though according to BVL #2's medical history, vestibular rehab history, and his answers to his post experiment questionnaire as well as from what we noticed with respect to his adaptation when he came to the lab for the experiment, he is still showing this hip EMG pattern even though he has learned to adapt and compensate to such a high degree. This would leave us to believe that his plant possibly may not be able to produce an EMG signal that would create the proper body segment sway at the hip even with his high degree of compensation. Therefore, adaptation may not be able to improve the weighted signal that is coming from the nervous system to create sway but may in fact be using other means to keep himself more stable than some of his other fellow bilateral vestibular patients.

## *Feedback Frequency Response Functions*

### *Closed Loop FRF from waist mechanical perturbation to body segment angles*

Figure 4.6 shows the influence of the waist mechanical perturbation on the kinematics of all four subjects. Control #1 demonstrates what would be expected, where both her trunk and leg are in phase at lower frequencies and slowly grow out of phase at the higher frequencies, when a hip strategy becomes necessary. Control #2 on the other hand has the leg segment leading the trunk segment across all frequencies. This is not expected for a control, though his height may be an influence. At being around nearly six feet tall it may be that the waist motor had much more of an influence on his legs and not his trunk due to the size of the leg and trunk segments. Since the waist motor was attached to a belt on the waist it would be easier for the movement of the waist motor and spring to have an influence on the movement of the leg segment because it is positioned lower on the body. With his trunk segment being much longer it may be harder for the waist motor to have an influence on his trunk. Both controls do show a similar leg leading pattern in their phases at higher frequencies.

Both patients seem to show a legs leading pattern at the higher frequencies as well. Gain and phase patterns are fairly similar across all four where they decrease with increasing frequency. BVL #2 was age, gender and more importantly height matched to this control. Just as BVL #2 showed a lengthened separation of the two segments across frequencies so did BVL #1, though not as strongly. It could be that the height may have influenced BVL #2's ability to keep the leg and trunk segments in phase at the lower frequencies. He may have kept them more in phase at the lower frequencies than BVL



#1 because it would be easier for a BVL to keep the two segments in phase since it is harder for them to use a hip strategy. The split that is seen at the lowest frequency bin for both patients with BVL is hard to determine since those points are not significantly different from zero. Therefore, it could easily be that these patients with BVL have leg and trunk segments that are in phase at the lowest frequencies but it is not possible to determine with this lack of significance.

*Closed Loop FRF from shoulder mechanical perturbation to body segment angles*

In Figure 4.7 both controls seem to show a legs leading pattern to the shoulder motor at higher frequency bins. It also appears that the legs lead in the lower phase frequencies but caution is warranted with any interpretation here, as the responses at the lowest frequency bins are not significantly different from zero for both controls. Gains appear higher for the trunk than for the leg segment for both controls. Gain and phase plots for both of these subjects are a little more variable compared to the waist motor kinematic data as the lower frequency bins show little to no significance from zero. This could indicate that the shoulder motor does not have much influence at the lower frequencies, though its possible the same may be said for the waist motors as well since the lowest frequency bin also lacks significance for both controls.

The shoulder motor also appears to have less of a significant influence on the patients with BVL' kinematics as many of the data points show no significance from zero. All four subjects show a trunk leading pattern at the higher frequencies but BVL #1 appears to show this separation much later in the frequency distribution than the others. All other subjects, including BVL #2, show this separation of body segments around the

second or third frequency bin but only BVL #1 shows this separation starting at the fifth frequency bin. When looking back at Figure 4.6 this same pattern can be seen as well where all other subjects show a separation of segments around the second bin (taking the lack of significance at the first binned frequencies into account for these three). BVL #1 on the other hand does not show a separation of the body segments until around the fourth binned frequency. It is possible that BVL #1, due to her lack of compensation is trying to using only an ankle strategy until the last possible moment and save any movement around the hip till its absolutely necessary, which would be at the highest frequencies. This lack of separation is easily seen in her phase pattern in Figure 4.7 as both segments are exactly in phase for practically most of the frequency spectrum. This thought is also supported by pure observation when she came to visit the lab for the experiment. As she moved about her upper body was very stiff, as if it was impossible for his to move at the waist. She even admitted to doing this as she felt it helped not only to stable her for balance but it also helped to reduce her oscillopsia.

Shoulder motor kinematic data appears to be slightly less consistent for significance with the patients with BVL. This could be due to the position of the shoulder relative to the position of the waist motor. Perturbations at the waist can be interpreted by feedback from proprioception in the legs. Due to this perturbation's close proximity to the legs and further distance from the vestibular apparatus the nervous system may rely on the information coming from the legs more with regard to the perturbation to stay upright, especially since there is no vestibular system to rely on. The shoulder motor on the other hand is attached to a shoulder belt which has a spring connection located right between the shoulder blades. Any movement here would

normally be quickly interpreted by the vestibular system due to its close proximity. The movement created by the shoulder motor would be very hard for the proprioceptors in the leg to interpret since the propagation of that movement down the body may not even make it to the legs as the perturbation was so tiny. With a lack of vestibular interpretation and input with these patients this could make a response to a motor located this high up on the body harder and more variable.

*Closed Loop FRF from mechanical perturbation to weighted ankle EMG*

In Figure 4.8 both controls, for the first time, have larger error bars, for many of the frequencies. The waist perturbation has a higher gain than the shoulder perturbation for the weighted ankle EMG for both controls. The error bars for phase and gain are also smaller for the waist perturbation to ankle EMG than the shoulder perturbation to the ankle EMG. This could be because of the close proximity of the waist perturbation to the ankle muscles compared to where the shoulder perturbation is located.

BVL #1 has many more frequency bins that are less significant from zero compared to BVL #2. This again could be due to the adaptation difference between these two patients. The waist perturbation gains also seem higher than the shoulder perturbation gains for the BVLs as well and like the controls the error bars are also smaller for the gain and phase for the waist motor compared to the shoulder motor.

*Closed loop FRF from mechanical perturbation to weighted hip EMG*

For Figure 4.9 the controls show a gain that is higher for the waist motor compared to the shoulder motor for the weighted hip EMG. The BVL's show the opposite pattern, the gain for the shoulder motor is higher than the gain for the waist motor to hip EMG. Again, this must be interpreted with caution as the hip data for the patients with BVL shows little if any significance from zero. A possible reason that the patients with BVL have a higher gain for the shoulder motor perturbation to the weighted hip EMG is because of the lack of a functioning vestibular system. When the control subjects are perturbed with the shoulder motor the vestibular system can interpret this information regarding their changing position. The patients with BVL on the other hand do not have this vestibular system to fall back onto and need to rely on the feedback information that the shoulder perturbation may be supplying them (possibly touch or even proprioceptive information). Since there is no vestibular information to influence the movement about the hips for these patients their hip EMG ends up relying on the shoulder motor movement more to stay upright. The controls get information from the shoulder motor and the vestibular system's interpretation of how the body is moving. This combination may allow the nervous system to create a weighted hip signal that would rely more on the waist motor, possibly because the shoulder motor is not really giving any reliable position information to keep them upright, while the waist motor is giving more informative details of their position in space.

#### *Inferred open loop feedback FRF from body segments to weighted ankle EMG*

For both the controls and patients with BVL, in Figure 4.10, the frequency bins lack significance at many points, more so for the patients than for the controls, as would be expected. Control #1 is the only one who shows a legs leading pattern in her phase at the higher frequencies. From what Creath et al (2008) had found it would be expected that the patients with BVL would show a legs leading pattern but its still possible that it exists but can not be determined due to the lack of significance from zero for many of the data points. More data would need to be collected from these patients to determine whether or not this is the case.

#### *Inferred open loop feedback FRF from body segments to weighted hip EMG*

The control subjects' data for Figure 4.11 show a large lack of significance from zero for the trunk to hip EMG signal and it is only slightly improved for the leg to hip EMG signal. For both controls it appears that at the higher frequencies that their leg segments lead the trunk segment but again this statement must be approached with caution. The data for the patients with BVL is again non- significant from zero for all bins for both gain and phase plots. There does appear to possibly be a legs leading trunk pattern but again this must be approached with caution. Gains for BVL #1 are higher than Control #1 and gain for BVL #2 are higher than Control #2 but only at the higher frequency bins. It could be that due to the patients' lack of vestibular feedback input that the patients need to rely on the motors more to keep themselves balanced. All four subjects show the legs to hip EMG having a higher gain.

### *General conclusions and ideas for further research*

Overall, for all four subjects, plant and feedback dynamics do seem to be different. Plant phases seem to show a definite trunk leading pattern. BVL #1 showed the highest gains to vision, especially with the kinematic data as would be expected from Peterka's 2002 findings. It is possible that BVL #1's lack of compensation compared to BVL #2 is the reason for her larger increase in gain with an increase in frequency.

Weighted hip EMG lacked any significance for the patients unlike their controls, suggesting possible evidence for this patient population's inability to properly control their trunk segment.

Feedback dynamic results were not as clean with respect to the confidence interval error bars and this could possibly be due to the motor perturbations themselves, which will be discussed further later in this section. BVL #1 did appear to have her trunk and leg segments relatively in phase with each other during most of the frequencies unlike the other BVL and the controls, suggesting she was trying to only move about the ankle, a common strategy for many patients with BVL. Again, weighted hip EMG data was statistically insignificant from zero for the patients but this was also the case for the controls. A possible legs leading strategy may exist, as was found in Creath et al (2008) but more data collection would be needed in order to determine this.

Future research would require much more data collection with this patient population. As bilateral vestibular loss affects patients to varying degrees it makes it hard to group all collected patients into one averaged group, and therefore data analysis for individuals becomes more important. One possibility, once more patients have

participated, would be to investigate the differences between those patients who are better compensated than others. A way to determine would be to use a questionnaire (found in Appendix 3 of this paper) that allow one to figure out what physical activities, if any, the patients are still involved in. Comparing those two groups to controls would then allow for a comparison to see if staying physically active and going through rehabilitation can allow plant or feedback dynamics to become more like those of a control subject.

Rehabilitation for these patients at a physical therapy clinic may take weeks or even months and it involves many exercises that will leave the patient feeling possibly even worse then when they arrived, making going to the physical therapist less appealing for these patients. Research showing that persistent rehabilitation as well as regular physical activity improves balance and coordination could encourage these patients to continue through the physical therapy. Further identification of the specifics for the plant and feedback dynamics for this particular population could possibly open doors for other medical professionals in the vestibular rehabilitation field for finding better physical therapy activities and maybe even possibly lead towards and idea for a form of cure.

In the future a substitute for mechanical perturbations would be required. For this experiment the motors were under position control. From this experiment it would be suggested that force control motors be used to see if a “cleaner” response to the motors can be made.

## Appendix A

Page 1 of 2

Initials \_\_\_\_\_ Date \_\_\_\_\_

### **CONSENT FORM**

<b>Project Title</b>	<b><i>Multisensory Integration and Human Postural Control</i></b>
<b>Why is this research being done?</b>	<i>This is a research project being conducted by Dr. John Jeka at the University of Maryland, College Park. We are inviting you to participate in this research project because you are over 18 years of age and you have bilateral vestibular loss. The purpose of this research project is to investigate how sensory information influences how you stand.</i>
<b>What will I be asked to do?</b>	The procedures involve approximately 3.5 hours of testing during which you will stand as still as possible while surrounded by a visual images projected on large screens. You will also experience small motor perturbations. Your task is to maintain a standing posture while looking straight ahead during the entire trial. At the end of the trial, you will hear a tone. You may then sit down and relax for 2 minutes before the next trial. Up to nine small sensors that emit invisible red light (i.e., infrared) and twelve pairs of passive sensors to detect the electrical activity of muscles will be attached to your skin. Also, you will need to wear shorts and a short-sleeved or sleeveless shirt, but no socks or shoes in order for these sensors to be correctly placed. The skin on your legs will be cleaned, first with an alcohol swab and then with a clean, damp paper towel to ensure the best contact between the sensors and my skin. You understand that it may be necessary to shave the skin at the site of attachment to remove excessive body hair and insure proper contact of surface electrodes.
<b>What about confidentiality?</b>	<i>We will do our best to keep your personal information confidential. To help protect your confidentiality: (1) your name will not be included with the collected data; (2) a code will be placed on the collected data; (3) through the use of an identification key, the researcher will be able to link your data to your identity; and (4) only the researcher will have access to the identification key. If we write a report or article about this research project, your identity will be protected to the maximum extent possible.</i>  <i>Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.</i>
<b>What are the risks of this research?</b>	There is a slight possibility of losing your balance during the experiment. If you lose your balance, you can lean into the support harness which will prevent your fall. A technician will also be standing behind you to help prevent a fall.



<b>Project Title</b>	<b><i>Multisensory Integration and Human Postural Control</i></b>	
<b>What are the benefits of this research?</b>	<p><i>This research is not designed to help you personally, but the results may help the investigator learn more about postural control and the prevention of falls. We hope that, in the future, other people might benefit from this study through improved understanding of how people fall and prevent Injuries due to falls.</i></p> <p><i>For participating in this we will reimburse you for your travels as well as provide you with food, an extra \$100 and a one night's stay in a local hotel if needed.</i></p>	
<b>Do I have to be in this research? May I stop participating at any time?</b>	<p><i>Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.</i></p>	
<b>Is any medical treatment available if I am injured?</b>	<p><i>The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.</i></p>	
<b>What if I have questions?</b>	<p><i>This research is being conducted by Dr. John Jeka in the Department of Kinesiology at the University of Maryland, College Park. If you have any questions about the research study itself, please contact Dr. John Jeka at 301-405-2512 or <a href="mailto:jjeka@umd.edu">jjeka@umd.edu</a>.</i></p> <p><i>If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: <b>Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (e-mail) <a href="mailto:irb@deans.umd.edu">irb@deans.umd.edu</a>; (telephone) 301-405-0678</b></i></p> <p><i>This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.</i></p>	
<b>Statement of Age of Subject and Consent</b> [Please note: Parental consent always needed for minors.]	<p><i>Your signature indicates that:</i></p> <p><i>you are at least 18 years of age;</i></p> <p><i>the research has been explained to you;</i></p> <p><i>your questions have been fully answered; and</i></p> <p><i>you freely and voluntarily choose to participate in this research project.</i></p>	
<b>Signature and Date</b>	<b>NAME OF SUBJECT</b>	
	<b>SIGNATURE OF SUBJECT</b>	
	<b>DATE</b>	

## Appendix B

### BVL TELEPHONE SCREENING QUESTIONNAIRE

Date Screened: \_\_\_\_\_

**Participant's Name:** \_\_\_\_\_ **Code:** \_\_\_\_\_

Birth Date: \_\_\_\_/\_\_\_\_/\_\_\_\_ Age: \_\_\_\_\_ Phone #: (     ) \_\_\_\_\_ -  
\_\_\_\_\_

Address: \_\_\_\_\_  
\_\_\_\_\_

City, Prov: \_\_\_\_\_, \_\_\_\_\_ Postal Code \_\_\_\_\_  
\_\_\_\_\_

Best time to call: \_\_\_\_\_

Data Collection Booked: \_\_\_\_\_

**Height:** \_\_\_\_\_ **cm**     **Gender** M\_\_ F\_\_     **Weight:** \_\_\_\_\_ **kg**

Start of BVL \_\_\_\_\_

Cause of BVL \_\_\_\_\_

For the purposes of this questionnaire, a “fall” is defined as an incident in which you found yourself on the ground when you did not intend to be. A “near fall” is defined as an unintentional incident in which you lost your balance and *would have* fallen down *if* you had not received support from some nearby object (such as a handrail or piece of furniture) or person. If you slipped or tripped and ended up on the ground, or would have ended up on the ground without some external support, those incidents are classified as a “fall” or “near fall”.

Are you able to stand for at least 5 minute, without assistance?     - - - - Y\_\_

N\_\_

Are you able to walk at least 10 m (30 ft), without any assistance?     - - - - - Y\_\_

N\_\_

Do you live in a house or apartment? - - - - - Hou  
Apt

In the last month, have you ever had any episodes where you felt dizzy,  
unsteady or weak? - - - - - Y\_\_  
N\_\_

Do you have, or have you ever had, problems with falling? - - - - - Y\_\_  
N\_\_

**If Yes, then:**

Have you fallen during the past year? - - - - - Y\_\_ N\_\_

1.a. If yes, how many times? \_\_\_\_\_

1.b. If yes, were you ever injured as a result of a fall? Y\_\_  
N\_\_

Did you feel faint, dizzy, or weak before any of your falls? - - - - - Y\_\_ N\_\_

Did you faint or lose consciousness before any of your falls? - - - - Y\_\_ N\_\_

Have you experienced any near falls within the last year? Y\_\_  
N\_\_

If you answered yes, how many near falls have you had? \_\_\_\_\_

Have you noticed that you are definitely less steady than you were a year ago?  
Y\_\_ N\_\_

If you answered yes, what have you noticed that makes you think you are not as  
steady as you were a year ago?

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Is your vision (with glasses or lenses) sufficient enough for:

daytime driving? Y\_\_ N\_\_

watching TV?	Y__	N__
reading?	Y__	N__

Are you currently free of any acute illnesses (flu, pneumonia, etc.) and free of any illnesses or diseases that pose an immediate threat to your daily life? Y\_\_  
N\_\_

**Do you have or have you ever had:**

a) Paralysis ----- Y\_\_  
N\_\_

b) Epilepsy ----- Y\_\_  
N\_\_

c) cerebral palsy ----- Y\_\_  
N\_\_

d) multiple sclerosis ----- Y\_\_  
N\_\_

e) Parkinson's disease ----- Y\_\_  
N\_\_

f) Stroke ----- Y\_\_  
N\_\_

g) any other neurological disorder ----- Y\_\_  
N\_\_

describe \_\_\_\_\_

h) diabetes ----- Y\_\_  
N\_\_

i) problem with your vision that isn't corrected by glasses --- Y\_\_  
N\_\_

j) cataract surgery ----- Y\_\_  
N\_\_

k) a balance or coordination problem ----- Y\_\_  
N\_\_

- l) hearing problems ----- Y\_\_  
N\_\_
- m) constant ringing in your ears -----Y\_\_  
N\_\_
- n) ear surgery ----- Y\_\_  
N\_\_
- o) head injury tumor of brain or spinal cord ----- Y\_\_  
N\_\_
- p) peripheral neuropathy ----- Y\_\_  
N\_\_
- q) frequent numbness in legs or feet ----- Y\_\_  
N\_\_
- r) frequent dizziness ----- Y\_\_  
N\_\_
- s) claustrophobi ----- Y\_\_  
N\_\_

**Have you ever had any serious problems with your memory?** Y\_\_  
N\_\_

**Do you have any prosthetic limbs?** -----Y\_\_  
N\_\_

**Have you ever had a joint replacement or a joint fusion?** Y\_\_  
N\_\_

**Do you have difficulties performing any daily activities?** Y\_\_  
N\_\_

Which activities? \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

How much does the condition interfere with your activities?

**little mod a great deal**

**Do you have any conditions which limit the use of your arms or legs?**

Describe: \_\_\_\_\_

**Have you ever taken the caloric or rotating chair test? If so, what was the result?**

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Do you have or have you ever had :**

**Yes    No**

a)    problems with your heart or lungs	_____	_____
_____                      b)    high blood pressure	- - - - -	- - - - -
_____    _____		
c)    blood circulation problems                      - - - - -	_____	_____
_____		
d)    cancer                      - - - - -	_____	_____
_____		
e)    arthritis                      - - - - -	_____	_____
_____		
f)    rheumatism                      - - - - -	_____	_____
_____		
g)    back problems                      - - - - -	_____	_____
_____		

- h) a joint disorder - - - - - \_\_\_\_\_
- \_\_\_\_\_
- i) a muscle disorder - - - - - \_\_\_\_\_
- \_\_\_\_\_
- j) a bone disorder - - - - - \_\_\_\_\_
- \_\_\_\_\_

**Have you ever severely injured or had surgery on your**

- a) head - - - - - \_\_\_\_\_
- \_\_\_\_\_
- b) neck - - - - - \_\_\_\_\_
- \_\_\_\_\_
- c) back - - - - - \_\_\_\_\_
- \_\_\_\_\_
- d) pelvis - - - - - \_\_\_\_\_
- \_\_\_\_\_
- e) ankle, knee, or hip joints? - - - - - \_\_\_\_\_
- \_\_\_\_\_

**Have you ever broken any bones?**

\_\_\_\_\_

Which bone? \_\_\_\_\_

**Have you had any recent (specify)**

- a) illnesses - - - - - \_\_\_\_\_
- \_\_\_\_\_
- b) injuries - - - - - \_\_\_\_\_
- \_\_\_\_\_
- c) operations - - - - - \_\_\_\_\_
- \_\_\_\_\_

**Are you currently taking any medications (prescription or over-the-counter), or other drugs?**

[illegible]

Have any of these drugs made you feel dizzy, unsteady, or weak? Y\_\_  
N\_\_

**If the subject is recruited:**

- Bring a running shoe with him/herself at the time of the test
- Wear a dark short and sleeveless shirt
- Have his/her lunch with herself
- Do not drink any alcohol 24 hours prior to the test



## Appendix C

### **Follow up Questionnaire for BVL patients:**

*Please feel free to elaborate on any of the questions because the more answers we have the better! Thanks!*

How long have you had BVL?

Are you independent in self care activities (i.e. - taking a shower, cooking, brushing teeth, etc.)?

If “no” which ones give you difficulty?

Can you drive?

Daytime?

Nighttime?

Are you working? Occupation: \_\_\_\_\_

Please describe

How do you get yourself to your job?

If you no longer are working what was your occupation?

Are you on medical disability?

If you are a parent do you have difficulty performing parenting activities? If so which ones in particular?

Do you have difficulty with any of the following:

Watching TV?

Reading?

Being in stores or malls?

Being in traffic?

Using a computer?

Feel free to elaborate

Do you have difficulty walking up and down ramps, stairs and/or walking on grass?

Have you done physical therapy since the bilateral vestibular loss?

How long did you attend PT or how long have you been attending?

Please describe the exercises you performed?

Do you continue to do them at home?

Have you noticed any improvement in your ability to accomplish these activities since starting PT?

What physical activities did you do for fun before the BVL?

Have you continued to do any of those physical activities after the BVL? If so which ones?

Have you picked up any new physical activities since the BVL?

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